PB83-200188

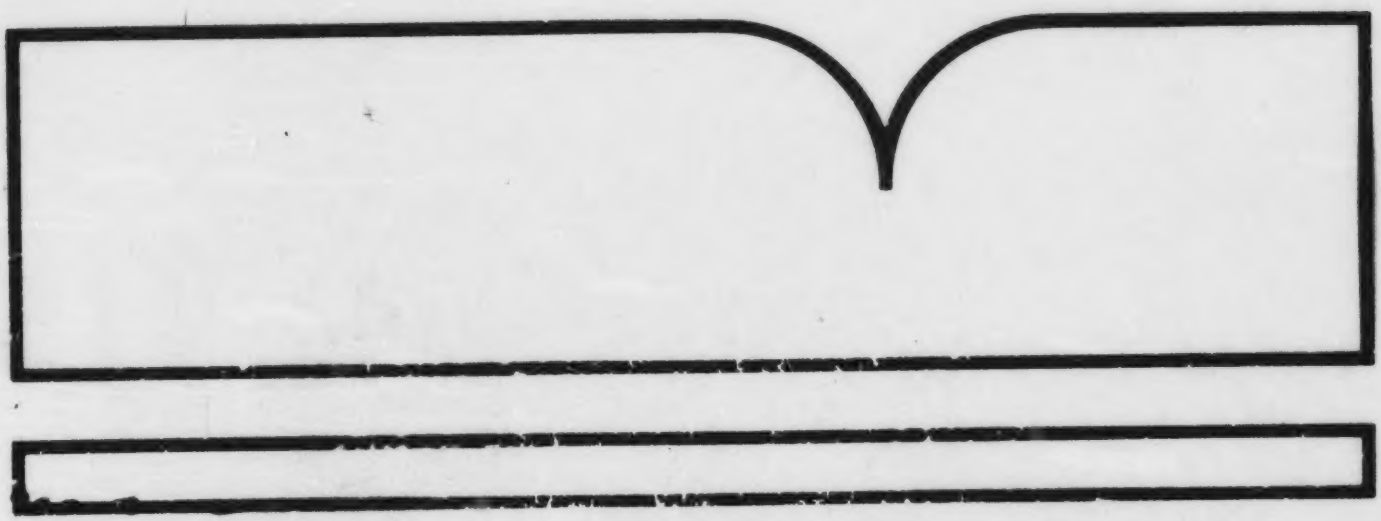
Survey of Industrial Applications of Aqueous-Phase Activated-Carbon Adsorption for Control of Pollutant Compounds from Manufacture of Organic Compounds

IT Enviroscience, Inc.
Knoxville, TN

Prepared for

Industrial Environmental Research Lab.
Cincinnati, OH

Apr 83



U.S. Department of Commerce
National Technical Information Service
NTIS

TYPING GUIDE SHEET
BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD, BEGIN SECTIONS HERE
6-1/2"
9-1/2"
BEGIN LAST LINE OF TEXT
3/8"
PAGE NUMBER
BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
EPA-267 (Cin.) (4-76)

PB83-200188

EPA-600/2-83-034
April 1983

SURVEY OF INDUSTRIAL APPLICATIONS OF AQUEOUS-PHASE ACTIVATED-CARBON ADSORPTION FOR CONTROL OF POLLUTANT COMPOUNDS FROM MANUFACTURE OF ORGANIC COMPOUNDS

by

William L. Troxler, Charles S. Parmele, and Douglas A. Barton
IT ENVIROSCIENCE
(FORMERLY TENNESSEE REGION OF HYDROSCIENCE, INC.)
9041 Executive Park Drive
Knoxville, Tennessee 37923

Contract No. 68-03-2568
Task No. T7009

Project Officer

Ronald J. Turner
Industrial Pollution Control Division
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/2-83-034		PB83 200188

4. TITLE AND SUBTITLE	5. REPORT DATE
Survey of Industrial Applications of Aqueous Phase Activated-Carbon Adsorption for Control of Pollutant Compounds from Manufacture of Organic Compounds	April 1983
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) W. L. Troxler, C. S. Parmele, C. A. Barton	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS IT ENVIROSCIENCE, INC. 9041 Executive Park Drive Knoxville, TN 37923	10. PROGRAM ELEMENT NO. CO6A1B
	11. CONTRACT/GRANT NO. 68-03-2568 (T-7009)
12. SPONSORING AGENCY NAME AND ADDRESS INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY OFFICE OF RESEARCH AND DEVELOPMENT U.S.ENVIRONMENTAL PROTECTION AGENCY CINCINNATI, OH 45268	13. TYPE OF REPORT AND PERIOD COVERED Final (4/79 - 3/80)
	14. SPONSORING AGENCY CODE EPA/600/12

15. SUPPLEMENTARY NOTES
A Survey of Vapor-Phase Activated Carbon Applications is Covered in a Separate Report

16. ABSTRACT

This study covers industrial use of activated carbon for aqueous-phase applications. The report includes full-scale, pilot and laboratory granular and powdered activated carbon performance data, as indicated by measurement of gross parameters such as TOC and COD.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Industrial waste treatment	Air Pollution Control	13B
Organic compounds	Vapor-phase adsorption	68A
Hydrocarbons	Wastewater Treatment	
	Carbon adsorption	

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
Release to Public	Unclassified	114
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

The objective of this study was to gather performance data on the current uses of activated carbon for treating both industrial wastewaters and vapor emissions from the manufacture and use of organic chemicals. This information is contained in two reports: one dealing with aqueous-phase applications and one with vapor-phase applications. Much of the basic information about carbon adsorption has appeared elsewhere in a variety of sources; these reports serve the purpose of bringing together the information in a single source. The data compiled by this survey can also be used to identify sites for sampling.

For further information on this subject, contact the Industrial Environmental Research Laboratory, Cincinnati, Ohio 45268

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati, Ohio

ABSTRACT

Activated-carbon adsorption has frequently been mentioned as an applicable technology for the organic chemical industry for satisfying the wastewater treatment objectives for the control of priority pollutants as specified in the Clean Water Act of 1977, which call for "best available treatment economically achievable" (BATEA) by July 1, 1983. This report reviews the current uses of activated carbon for the treatment of wastewaters generated during the manufacture of organic chemicals. A separate report on the use of vapor-phase carbon adsorption to control atmospheric emissions of organic chemicals has been prepared concurrently.

During the last decade many activated-carbon systems were installed for the treatment of industrial wastewater streams. These applications span several industries, with major applications in the organic chemical manufacturing, explosives, petroleum refining, and textile and carpet manufacturing industries. A review of the open literature, government reports, vendor literature, information available from chemical manufacturers, state agency files, and EPA files reveals that some degree of information is available on approximately 115 to 125 full-scale granular-activated-carbon systems and approximately 13 full-scale powdered-activated-carbon systems that are now or have been operating in the United States.

The results of this survey showed that there are numerous gaps in the available data, especially those pertaining to the performance and economics of removing specific compounds such as the priority pollutants. This is true in spite of the special efforts that were made during this survey to collect data concerning the wastewater stream characteristics, the major engineering design features of the adsorption system, the effluent quality attainable, and the economics involved. The available data have been compiled in a consistent format in order to facilitate retrieval of the available information pertaining to the effectiveness and economics of carbon adsorption as a waste treatment technology for the organic chemical industry.

This report has been prepared by Hydroscience, Inc., in fulfillment of Contract No. 68-03-2568. It covers the period from April, 1979 to January 1980.

CONTENTS

		Page
FOREWORD		iii
ABSTRACT		iv
FIGURES		vi
TABLES		vii
I	INTRODUCTION	1
II	CONCLUSIONS	3
III	RECOMMENDATIONS	6
IV	DISCUSSION OF RESULTS	7
V	PROPERTIES OF ACTIVATED CARBONS	9
VI	WASTEWATER CHARACTERISTICS THAT AFFECT ADSORPTION BY ACTIVATED CARBON	18
VII	DISCUSSION OF GRANULAR-ACTIVATED-CARBON PILOT-PLANT AND BENCH-SCALE DATA	29
VIII	DISCUSSION OF FULL-SCALE INDUSTRIAL APPLICATIONS OF GRANULAR-ACTIVATED-CARBON ADSORPTION	43
IX	DISCUSSION OF POWDERED-ACTIVATED-CARBON FULL-SCALE SYSTEMS AND PILOT STUDIES	76
X	DATA SOURCES	89

APPENDICES

A	BENCH-SCALE AND PILOT-PLANT GRANULAR-ACTIVATED-CARBON DATA	105
B	FULL-SCALE GRANULAR-ACTIVATED-CARBON-ADSORPTION SYSTEM DATA	161
C	POWDERED-ACTIVATED-CARBON DATA	239

FIGURES

Number		Page
1	Phenol Adsorption Isotherms for Various Types of Carbon at 22°C	11
2	Downflow Pressure Drop vs Hydraulic Loading Rate	12
3	Bed Expansion As a Function of Hydraulic Loading Rate	13
4	Effect of Molecular Weight on Amenability of Adsorption of Organic Acids	22
5	Effect of Molecular Weight on Amenability of Adsorption of Alcohols	23
6	Effect of Molecular Weight on Amenability of Adsorption of Esters	24
7	Evaluation of Bench-Scale Carbon Column Data	32
8	Evaluation of Bench-Scale Carbon Column Data	33
9	Breakthrough Curve for Bio-Treated Wastewater	37
10	Binary Component Adsorption Data	38
11	Breakthrough of Components in Mixture	40
12	Frequency Distribution of Contact Times	64
13	Frequency Distribution of Hydraulic Loading Rates	65
14	Effect of Powdered Carbon on Effluent TSS	86

TABLES

Number		Page
1	Properties of Several Commercially Available Granular Activated Carbons	15
2	Properties of Several Commercially Available Powdered Activated Carbons	16
3	Amenability of Typical Organic Compounds to Activated-Carbon Adsorption	19
4	Relative Amenability to Carbon Adsorption of Typical Petrochemical Wastewater Constituents	21
5	Influence of Substituent Groups on Adsorbability	25
6	Comparison of Multi-Component Isotherm Data with Single-Component Data	27
7	Adsorption Isotherm Survey of SIC-2818, Industrial Organic Chemicals	28
8	Comparison of Activated-Carbon Capacity in Isotherm Tests vs Capacity in Column Test	30
9	Activated-Carbon Loading of Sodium Nitrophenol (SNP) as a Function of Bed Depth	35
10	Comparison of Single-Solute Isotherm Loading with Binary-Component Column Loading	39
11	Granular-Activated-Carbon Adsorption in Pilot- and Bench-Scale Tests	42
12	Companies Reported to Have Experience with Full-Scale Granular-Activated-Carbon Systems	44
13	Design Characteristics and Operational Parameters for Full-Scale Granular-Activated-Carbon Systems	48
14	Carbon Usage Data and Cost Data for Full-Scale Granular-Activated-Carbon Systems	49
15	Contaminant Removal Performance Data for Full-Scale Granular-Activated-Carbon Systems	50
16	Compounds Reported in Waste Streams Being Treated by Full-Scale Granular-Activated-Carbon Units	51
17	Effect of Regeneration on Bituminous Coal Carbon and Its Performance at British Petroleum Corporation Refinery	68

TABLES (Continued)

Number		Page
18	Isotherm Comparison of Performance of Virgin and Regenerated Carbon Used at British Petroleum Corporation Refinery, Marcus Hook, PA	68
19	Hercules Carbon-Adsorption System Operating Cost	71
20	Atlantic Richfield Carbon-Adsorption System Operating Cost	72
21	Reichhold Carbon-Adsorption System Operating Cost	73
22	British Petroleum Corporation Carbon-Adsorption System Operating Cost	73
23	Dow Carbon-Adsorption System Operating Cost	74
24	Installed Capital Costs of Reactivation Systems	75
25	Operating Costs of Reactivation Systems	75
26	Companies Reported to Have Experience with Full-Scale Powdered-Activated-Carbon Systems	78
27	Comparison of Full-Scale Test Data with Bench-Scale Data from Du Pont Chambers Works for Period 3/2/77 Through 3/26/77	80
28	Du Pont Chambers Works Full-Scale Test Data for Period 4/26/77 Through 3/26/77	81
29	Summary of Powdered-Activated-Carbon (PAC) Addition Trials at Sun Oil Company Refinery, Corpus Christi, TX	84
30	Effect of Powdered Carbon on Daily Average Effluent Suspended Solids at Sun Oil Company Refinery, Corpus Christi, TX	84
31	Effect of Powdered Carbon on Daily Average Effluent COD at Sun Oil Company Refinery, Corpus Christi, TX	85
32	Effect of Powdered Activated Carbon on Daily Average Effluent BOD_5 at Sun Oil Company Refinery, Corpus Christi, TX	85

I. INTRODUCTION

The major objective of this study was to gather performance data on the current use of activated carbon for treating wastewaters from the manufacture of organic chemicals. This information is to provide a technical basis for evaluating this technology in the establishment of guidelines defining "best available technology economically achieveable" (BATEA).

Adsorption by activated carbon is recognized as a highly efficient process for the removal of some classes of organic compounds from wastewater. The use of carbon adsorption is widespread for the treatment of compounds that may be toxic or refractory in nature. Adsorption may also be effective in removing organics from waste streams to very low concentrations. Activated-carbon systems are generally tolerant of varying or intermittent flow conditions.

Activated-carbon adsorption cannot, however, be used as a panacea. Some classes of organic compounds are simply not amenable to carbon adsorption. Others, which may have low loading capacity, will result in short carbon service time and excessive regeneration costs. Weakly adsorbed compounds may be temporarily retained and subsequently displaced by a more strongly adsorbed compound. This phenomenon of chromatographic displacement means that activated carbon systems are not always tolerant of waste concentration changes because they can lead to effluent concentrations of weakly adsorbed species that are higher than the influent concentration. These limitations must be given serious consideration when activated carbon is evaluated for removal of specific compounds from industrial waste streams.

The work program for this investigation includes documentation of full-scale applications of activated-carbon adsorption and collection of data defining the effectiveness of carbon adsorption in controlling wastewater discharges from the organic chemical industry. Data from pilot and laboratory investigations were also collected to supplement information gathered from full-scale systems.

In order to evaluate the effectiveness of activated-carbon adsorption in treating wastewaters from the manufacture of organic chemicals, the following criteria must be considered.

1. Influent waste characteristics
2. Effluent quality
3. Pretreatment requirements
4. Adsorption process equipment configuration
5. Equipment design characteristics
6. Hydraulic conditions
7. Carbon characteristics
8. Carbon regeneration
9. Capital costs
10. Operating costs

Activated carbon may be used in either a granular or a powdered form. Granular carbon is employed in packed, expanded, or fluidized beds, whereas powdered carbon is generally added to a biological treatment system. Due to the inherent differences in the mode of contacting the carbon with the wastewater stream, granular and powdered carbon systems are discussed separately.

Data for pilot- and bench-scale studies of granular-activated-carbon adsorption have been abstracted and are included with this report as Appendix A. Appendix B represents information gathered for full-scale granular-activated-carbon systems. Data for both pilot- and full-scale applications of powdered-activated-carbon systems are included in Appendix C.

An evaluation of the data collected during this study is divided into five main categories:

1. Properties of activated carbons.
2. Characteristics of the wastewater that affect adsorption.
3. Discussion of pilot and laboratory granular-activated-carbon studies.
4. Discussion of data from full-scale granular-activated-carbon systems.
5. Discussion of data from pilot studies and full-scale applications of powdered activated carbon.

II. CONCLUSIONS

1. Information gathered from a variety of sources indicates that there are presently over 100 domestic granular-activated-carbon systems used in treating industrial wastewaters. Some degree of information is available defining design characteristics, operational parameters, influent wastewater stream composition, and effluent quality for approximately 45 of these systems. Limited information is available on an additional 80 applications, with indications that there are up to 20 more applications that cannot be identified because of confidentiality restrictions.

2. The data base for full-scale applications in many instances is incomplete for two distinct reasons. For many applications essential operating parameters or pollutant removal characteristics have not been generated or not reported; and, when the data were generated, they were often considered to be confidential. The utility of existing published data is often limited to identifying the location of applications. Performance and cost data are often absent or are estimates that have not been verified. The value of these data bases will increase in the future as more data are developed and made available in a form that facilitates retrieval via computer.

3. Granular activated carbon has been demonstrated as a versatile technology for treating organically contaminated wastewater from a variety of sources. It has been used for pretreatment of process waste streams, in conjunction with other processes as a complete physical-chemical treatment system, or as a tool for upgrading effluent from a biological treatment system. Granular-carbon adsorption with in-place nondestructive regeneration has been used as a resource recovery technique to complement other physical separation technologies.

4. Performance data for carbon-adsorption systems, as indicated by measurement of gross parameters, such as BOD_5, TOC, and COD, can be best summarized in terms of ranges of removal efficiencies. These were 42-99% for TOC, 40-99% for COD, 25-95% for BOD. It should be recognized that removal efficiences as measured by gross parameters can be poor indicators of wastewater treatment performance especially when the system was designed for removal of color or specific components.

5. With the exception of phenol, the data on removal of specific compounds by full-scale granular-activated-carbon systems are, in general, very limited. Although a wide variety of compounds have been reported in wastewater streams being treated by carbon adsorption, there are relatively few cases where both the operating characteristics of the carbon-adsorption system and the composition of the wastewater stream are well defined. At the time many of these units were installed, regulations were concerned only with control of gross parameters. Although information regarding performance data were often incomplete, available data indicated that removal efficiencies for full-scale granular-activated-carbon adsorption systems ranged from 11-99.9% for a wide variety of components. Removal efficiencies for specific compounds were greater than 90% for three-fourths of the entries in Table 16 for which both influent and effluent concentrations were reported.

6. The degree of organic removal varies widely from plant to plant and for time with a given plant. Differences in performance as a function of time were attributed to variations in influent wastewater characteristics and changes in activated-carbon characteristics following repeated regeneration cycles.

7. Very few comprehensive studies have been published within the last five years that address the economics of wastewater treatment by granular activated carbon. During the period 1971 to 1974, several demonstration projects were operated from which extensive capital and operating costs were derived. During this period operating costs were found to vary from $0.07 to $0.62 per cubic meter of wastewater treated ($0.28 to $2.98 per 1000 gal).

8. Operating data for full-scale plants using powdered activated carbon are limited. The available information is not sufficient to conclude that powdered-carbon treatment systems may yield organic contaminant removals comparable to those obtained in granular-carbon systems.

9. Powdered-carbon systems have low capital costs relative to costs for granular-carbon systems. Operating costs are heavily dependent on carbon losses during regeneration. At the present time there is only one known full-scale industrial installation regenerating powdered carbon.

10. Laboratory studies conducted on single-solute samples indicate that organic compounds differ widely in their amenability to adsorption. Molecular weight, structure, polarity, and solubility are the major factors affecting the degree of adsorption.

11. Although no direct comparisons were made, adsorption capacities of activated carbons as determined by isotherm tests are generally higher than capacities obtained in column studies. High-removal efficiencies reported for isotherm tests are often accomplished by using economically unrealistic quantities of carbon and extensive contact times.

12. Dynamic column effects, such as competitive adsorption and chromatographic elution of compounds, cannot be predicted from isotherm tests. Data on adsorption of a specific compound from a mixed wastewater steam cannot be extrapolated for the same component in a wastewater stream of differing composition.

13. Significant performance differences exist among different activated carbons, in terms of both adsorptive capacity and hydraulic behavior. In order to make valid comparisons between quantitative adsorption data, a careful review of the bases is required to assure that the data were generated under identical conditions.

III. RECOMMENDATIONS

1. Data regarding the removal of specific components from complex industrial wastewater streams should be collected by sampling existing full-scale adsorption systems or by pilot-scale testing of actual wastewaters. The data compiled by this survey can be used as a screening tool to identify potential sampling sites where full-scale applications are removing a given compound. The survey also can be used to identify pilot-scale data that are now available for given compounds. The results of this survey should be supplemented by the results of the EPA-sponsored pilot-plant testing program to evaluate the removal of specific organic contaminants from wastewaters by activated-carbon adsorption. The data from that program have not been included in this survey because they have not been released for publication.

2. In order to assess the applicability of activated-carbon adsorption to a particular wastewater, a column study of the wastewater in question must be conducted that addresses factors such as the concentrations of specific components and their variability with time, the contact time, the hydraulic loading rate, the bed depth, the breakthrough curve characteristics, and the carbon adsorptive capacity, plus the merits of competitive carbons.

3. When column studies are conducted, regenerated carbon should be used to develop realistic estimates of the carbon performance. Data should be collected to define the changes in performance of the activated carbon as a function of repeated regenerations. Nondestructive regeneration techniques should also be considered as an alternative to thermal regeneration when possible.

IV. DISCUSSION OF RESULTS

Although this survey represents a compilation and review of many data sources, it does not completely describe all the full-scale aqueous-phase applications of activated-carbon adsorption. To do this (assuming that it is possible at all) would require a greater level of effort than was funded. The success of this survey was limited by several factors:

1. Identification of all full-scale applications was not possible. Some companies view the use of adsorption as proprietary and will not divulge any information. Carbon suppliers and equipment vendors were more cooperative but they, too, were unable to identify unpublished applications because of secrecy agreements with their clients. One hundred and twelve full-scale applications have been specifically reported. Data for 13 systems have been collected for which neither company name nor plant location is known, and the indications are that there are up to 20 more systems for which the only information that could be obtained was that they exist. Although some overlap is known to exist between these three categories of applications, the extent of the overlap is difficult to define.

2. Data for the identified systems are not complete, especially with respect to removal efficiencies for specific components and to cost data. In many cases these data are simply not available because analytical work has not been performed to identify specific components. In other cases companies will not release data on performance or costs because they consider these data to be proprietary. Some of these confidential data have been collected by the EPA and its contractors. However, these data are not included in this survey because too much effort was required to access these data. It was better to allocate the effort for this survey to collecting information that the EPA didn't already have. It would have also been difficult to combine these confidential data with nonconfidential data from other sources in an informative manner without jeopardizing the confidentiality of the data.

3. Existing data bases were often found to be incomplete or compiled in a manner which made information retrieval difficult. This problem will be

partially solved as more computerized data files are established (at least one will be brought on-line in 1980) and as gaps in existing data banks are identified and closed.

In this survey an attempt was made to strike a reasonable balance between the effort required to collect information and the amount of data that was collected. It is believed that a good balance was achieved and that the point of diminishing returns was approached. The ability to collect additional data on full-scale systems will be more a function of the availability of proprietary information than of the effort expended to get these data.

V. PROPERTIES OF ACTIVATED CARBONS

A. RAW MATERIALS

The major commercial brands of activated carbon used in industrial wastewater treatment vary both in the raw materials from which they are manufactured and in the manufacturing process itself. Consequently, properties of different carbons vary widely, and the selection of a particular carbon for a wastewater treatment application depends on the chacteristics of the wastewater and the hydraulic mode to be used in contacting the carbon with the wastewater stream.

Most of the activated carbon used in industrial wastewater treatment is manufactured from bituminous coal, lignite, petroleum coke, or wood. The raw materials used for producing activated carbon must have an inherently porous structure.

B. MANUFACTURING PROCESS

The process for producing activated carbon from a raw material consists of dehydration, carbonization, and activation. Dehydration is carried out at approximately 170°C. The carbonization step, which is done at about 275°C, causes the raw material to be volatilized to tar, methanol, and other by-products. The third step, activation, generally takes place in the range of 400—1000°C. The activation step is accomplished by introducing an oxidizing gas, such as air, steam, or carbon dioxide, into the activation chamber. The activation step enlarges the pores in the carbonized materials and increases their number sufficiently to provide a high adsorptive capacity.

C. ADSORPTIVE CAPACITIES

Activated carbons are characterized by measurements of both their adsorptive capacity and their physical properties. Adsorptive capacity for a specific component is generally expressed by an adsorption isotherm. The isotherm is the relationship, at a given temperature, between the amount of substance adsorbed and the concentration remaining in the liquid. Procedures for conducting isotherm tests are well documented and are not repeated in this report.

Isotherm tests can be a useful tool for making qualitative evaluations of different carbons for adsorption of specific components from a given waste

stream. Perrotti (88)* conducted isotherm tests with 12 different carbons to determine the capacity of each for the adsorption of phenol. As shown by Figures 1(a) and (b), adsorptive capacities of different carbons vary widely.

In addition to isotherm tests there are several other tests that yield insight into the relative removal capacities of activated carbons. The iodine number is an indicator of the activated carbon's affinity for adsorption of small molecules such as iodine. The iodine number is defined as the number of milligrams of iodine adsorbed per gram of carbon in equilibrium with a residual 0.02 N iodine solution. The iodine number measures micropores having an effective radius of less than 20 A. The molasses number is generally correlated with the ability of the activated carbon to adsorb relatively large molecules. It is a measure of the adsorptive capacity of a carbon for color bodies in a specified molasses solution. The molasses number yields a quantitative estimate of the volume of the transitional pores in the range of 20 to 500 A.

D. PHYSICAL CHARACTERISTICS

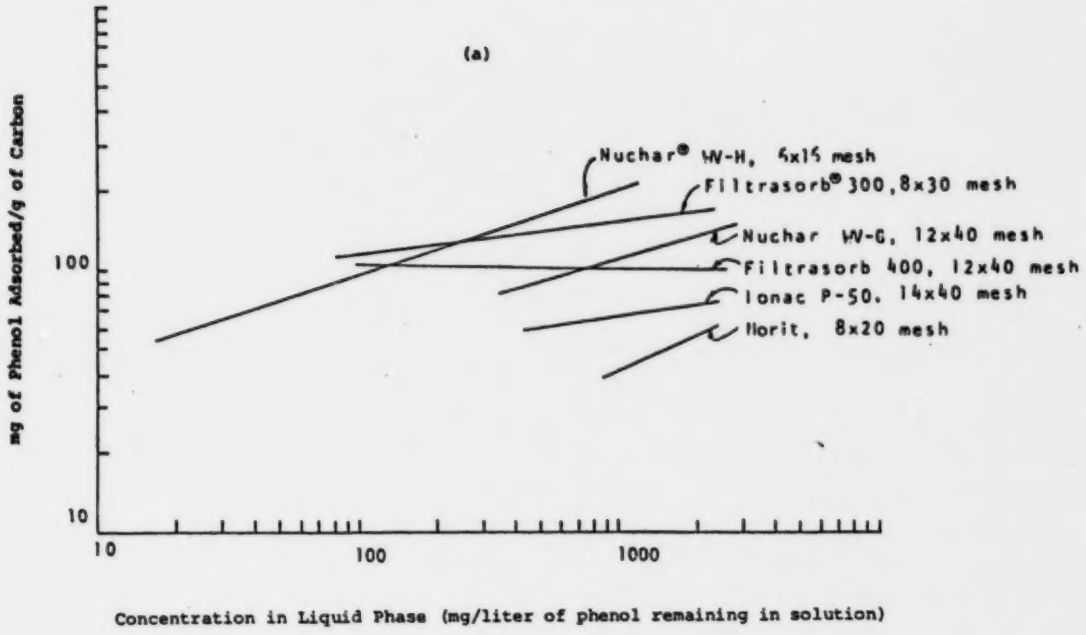
Physical properties that must be considered when an activated carbon is specified for a specific application include the total surface area, particle size, bulk density, and abrasion resistance.

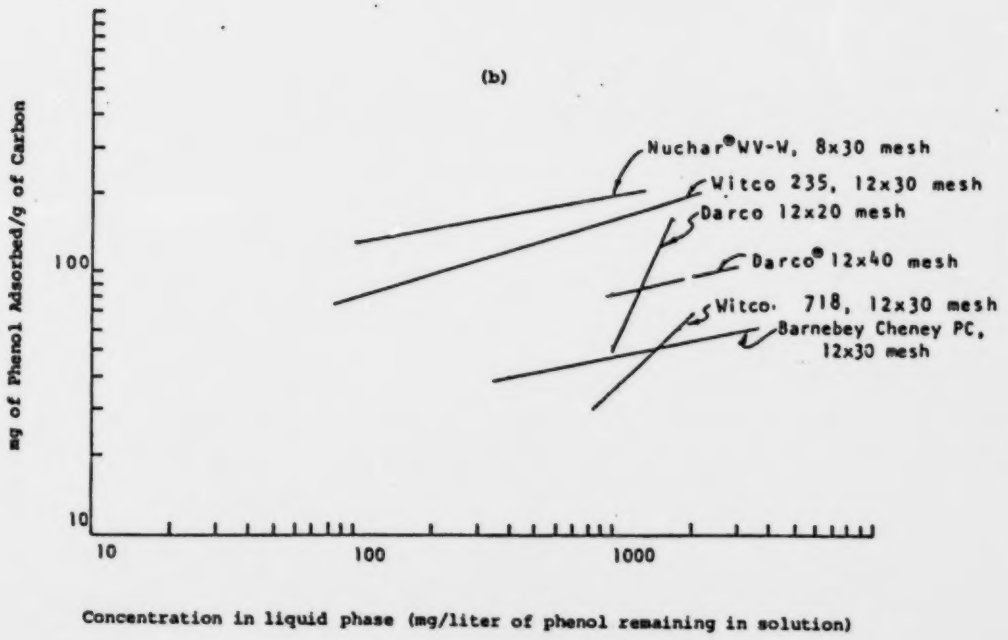
Total surface area is expressed as the surface area per unit weight of carbon. Total surface area is normally determined from the nitrogen isotherm by the Brunauer, Emmett, and Teller (BET) method. Major commercial brands of activated carbon generally have a surface area in the range of 600—1100 m^2/g.

Activated carbon may be used in either a powdered or a granular form. The most common sizes of granular activated carbon used in industrial wastewater treatment are 8 X 30 and 12 X 40. Particle size distribution is critical in terms of head loss characteristics and bed expansion during backwash operations. Pressure-drop and bed expansion characteristics for several different granular carbons are presented in Figures 2 and 3.

---

*See Sect. X, Data Sources, for references cited in this report.





Figures 1a and b. Phenol adsorption isotherms for various types of carbon at 22°C (adapted from ref 88)

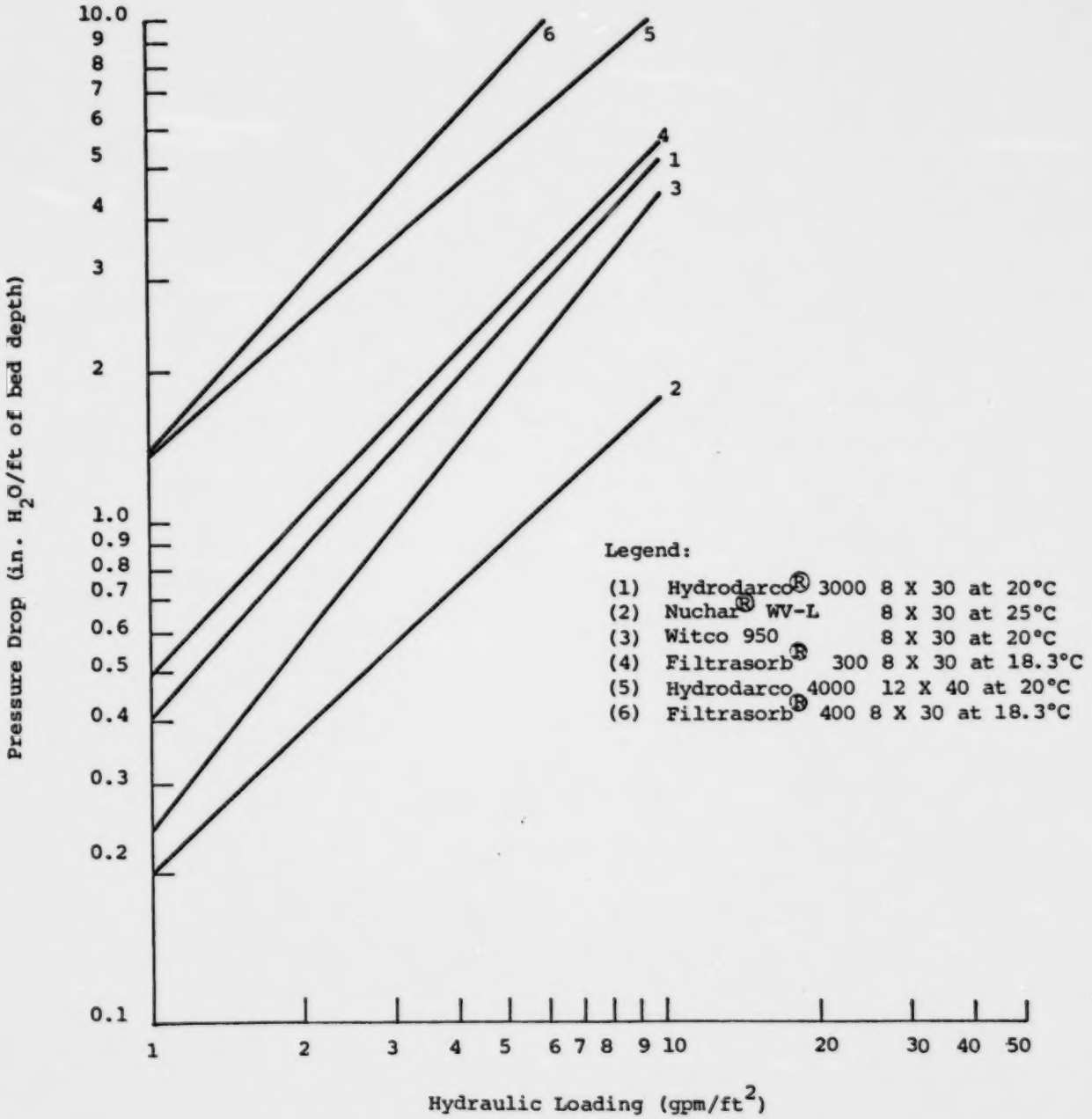


Figure 2. Downflow pressure drop vs hydraulic loading rate

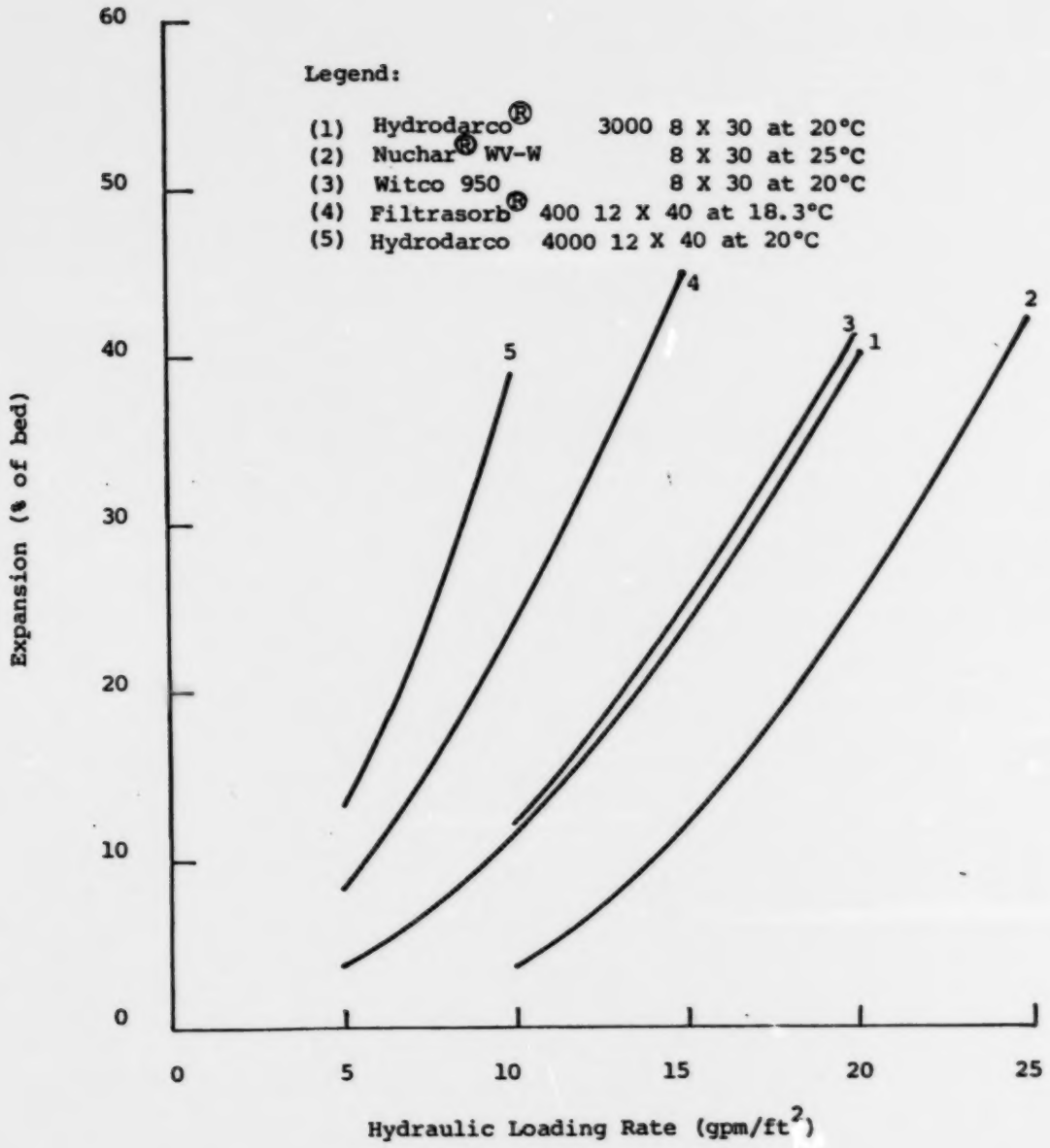


Figure 3. Bed expansion as a function of hydraulic loading rate

Bulk density, which is usually expressed as pounds per cubic foot, is a function of the raw material from which the carbon was manufactured and of the particle size distribution. Carbons manufactured from lignite generally have the lowest bulk density, whereas carbons manufactured from petroleum coke and bituminous coal have slightly higher bulk density values.

The abrasion number of a granular carbon is a measure of the resistance of the carbon to mechanical degradation. It has been reported (105) that abrasion test numbers are unreliable, not reproducible, and of limited value in specifying carbon characteristics.

The properties of several commerical granular activated carbons are summarized in Table 1. Table 2 contains similar data for powdered carbons.

E. SUMMARY

Activated carbons differ widely in both adsorptive capacities and physical characteristics. Based on data collected during a comprehensive literature review, Matthews (122) states that several authors have found no useful correlation between surface area and/or the ability to adsorb specific model substances. Therefore index numbers can be misleading, although they may have merit for initial screening (122).

Quantitative performance data are comparable only when tests are carried out under identical operating procedures. Although activated-carbon vendors provide specifications and typical properties for their products, test procedures may vary from vendor to vendor.

The carbon selected for a specific application is often based solely on tests of adsorptive capacity, but physical properties are equally important. Full-scale operating experience has indicated that the replacement of carbon lost because of attrition during handling is generally a major operating expense (23, 51). Although all carbons exhibit changes in characteristics following repeated regeneration cycles, DeJohn has reported that the degree of change is primarily a function of the raw material from which the carbon is manufactured (16).

TABLE 1. PROPERTIES OF SEVERAL COMMERCIALLY AVAILABLE GRANULAR ACTIVATED CARBONS[a]

	ICI Americas Hydrodarco 3000	Calgon Filtrasorb 300 (8 X 30)	Westvaco Nuchar WV-L (8 X 30)	Witco[d] 517 (12 X 30)
Physical Properties				
Surface area, m^2/g (BET)	600--650	950--1050	1000	1050
Apparent density, g/cc	0.43	0.48	0.48	0.48
Density, backwashed and drained, lb/ft^3	22	26	26	30
Real density, g/cc	2.0	2.1	2.1	2.1
Particle density, g/cc	1.4--1.5	1.3--1.4	1.4	0.92
Effective size, mm	0.8--0.9	0.8--0.9	0.85--1.05	0.89
Uniformity coefficient	1.7	1.9 or less	1.8 or less	1.44
Pore volume, cc/g	0.95	0.85	0.85	0.60
Mean particle diameter, mm	1.6	1.5--1.7	1.5--1.7	1.2
Specifications				
Sieve size (U.S. std. series)				
Larger than No. 8, max %	8	8	8	NA
Larger than No. 12, max %	NA	NA[b]	NA	5
Smaller than No. 30, max %	5	5	5	5
Smaller than No. 40, max %	NA	NA	NA	NA
Iodine number	650	900	950	1000
Abrasion No., minimum	c	900	950	85
Ash, %	c	8	7.5	0.5
Moisture as packed, max %	c	2	2	1

[a]From ref 105.

[b]Not applicable to this size of carbon.

[c]No available data from the manufacturer.

[d]Witco 517 is now designated Witcarb 950 by the manufacturer.

TABLE 2. PROPERTIES OF SEVERAL COMMERCIALLY AVAILABLE POWDERED ACTIVATED CARBONS

	ICI Americas Hydrodarco H	ICI Americas Hydrodarco C	Westvaco Nuchar S-A	Westvaco Nuchar SA-15
Physical Properties				
Apparent density (kg/m^3)	706	706	385--415	385--415
Apparent density (lb/ft^3)	44	44	24--26	24--26
Ash (%)			4--8	15 max
Surface area (m^2/g)	475	550	1400--1800	1400--1800
Total pore volume (m^3/g)			2.2--2.5	2.2--2.5
Water solubles (%)	3.5	5.5	3--4	
Through 100 mesh (%)			95--100	95--100
Through 200 mesh (%)			85--95	85--95
Through 325 mesh (%)	70 min	70 min	65--85	65--85
Specifications				
Iodine number			800 min	800 min
Molasses decolorizing index			14 min	15 min
Molasses RE, dry basis	40	95		
Moisture, as packed (%)			10 max	10 max
pH	10.5	10.5	4--6	3--6

The selection of an activated carbon for a specific application cannot be considered apart from the development of the appropriate engineering methods for its employment (122). Ford (107) has suggested several criteria that should be considered when selecting an activated carbon for a specific application. In general, the selected carbon should

1. have the adsorption capacity to meet effluent requirements,
2. incur minimum losses during carbon transport and regeneration,
3. have good hydraulic characteristics with respect to head loss or pressure drop,
4. represent the most cost-effective means of accomplishing the prescribed task.

VI. WASTEWATER CHARACTERISTICS THAT AFFECT ADSORPTION BY ACTIVATED CARBON

A. GENERAL

The adsorbability of specific compounds from pure-solute solution by activated carbon can be classified to a limited extent. In general, polar, low-molecular-weight organics with high degrees of solubility have been found to be poorly adsorbed. Conversely, nonpolar, high-molecular-weight organics with limited solubility generally tend to be preferentially adsorbed. However, there is an upper limit of molecular size above which adsorption is adversely affected. At some point, diffusion of large molecules within the small pores of the activated carbon particle is impeded by the carbon pore size. Tables 3 and 4 give independent evaluations of the adsorbability of many organic compounds. Figures 4, 5, and 6 demonstrate the effect of molecular weight on the adsorbability of select groups of organic acids, alcohols, and esters respectively.

B. MOLECULAR STRUCTURE

In addition to polarity, several other aspects of molecular structure affect adsorbability. In general, branched-chain compounds are more adsorbable than straight-chain compounds. Type and location of substituent groups also affect the degree to which a compound may be adsorbed from solution. Table 5 gives some general quidelines as to how substituent groups affect adsorbability.

C. EFFECT OF pH

The effect of pH on carbon-solute equilibrium varies significantly from compound to compound. Adsorption isotherms for some compounds are affected dramatically, whereas others show no significant change as a function of pH. Dissolved organics generally adsorb most efficiently at that pH which imparts the least polarity to the molecule. For example, phenol, a weak acid, can be expected to adsorb best at low pH values, whereas amines exhibit better adsorption characteristics at higher pH values.

D. TEMPERATURE EFFECTS

Adsorption reactions are generally exothermic; therefore lower temperatures have been reported (107) to favor adsorption. However, the author stated that very little information has been found in the literature that documents significant shifts in adsorbability within the range of temperatures normally encountered in wastewater treatment applications.

TABLE 3. AMENABILITY OF TYPICAL ORGANIC COMPOUNDS TO ACTIVATED-CARBON ADSORPTION* TEST CONDITIONS: 5 g OF WESTVACO WVG CARBON PER LITER OF SOLUTION

Compound	Molecular Weight	Aqueous Solubility (%)	Concentration (mg/liter)		Adsorbability	
			Initial	Final	g of Compound/ g of Carbon	Reduction (%)
Alcohols						
Methanol	32.0	∞	1,000	964	0.007	3.6
Ethanol	46.1	∞	1,000	901	0.020	10.0
Propanol	60.1	∞	1,000	811	0.038	18.9
Butanol	74.1	7.7	1,000	466	0.107	53.4
n-Amyl alcohol	88.2	1.7	1,000	282	0.155	71.8
n-Hexanol	102.2	0.58	1,000	45	0.191	95.5
Isopropanol	60.1	∞	1,000	874	0.025	12.6
Allyl alcohol	58.1	∞	1,010	789	0.024	21.9
Isobutanol	74.1	8.5	1,000	581	0.084	41.9
t-Butanol	74.1	∞	1,000	705	0.059	29.5
2-Ethyl butanol	102.2	0.43	1,000	145	0.170	85.5
2-Ethyl hexanol	130.2	0.07	700	10	0.138	98.5
Aldehydes						
Formaldehyde	30.0	∞	1,000	908	0.018	9.2
Acetaldehyde	44.1	∞	1,000	881	0.022	11.9
Propionaldehyde	58.1	22	1,000	723	0.057	27.7
Butyraldehyde	72.1	7.1	1,000	472	0.106	52.8
Acrolein	56.1	20.6	1,000	694	0.061	30.6
Crotonaldehyde	70.1	15.5	1,000	544	0.092	45.6
Benzaldehyde	106.1	0.33	1,000	60	0.188	94.0
Paraldehyde	132.2	10.5	1,000	261	0.148	73.9
Amines						
Di-N-Propylamine	101.2	∞	1,000	198	0.174	80.2
Butylamine	73.1	∞	1,000	480	0.103	52.0
Di-N-Butylamine	129.3	∞	1,000	130	0.174	87.0
Allylamine	57.1	∞	1,000	686	0.063	31.4
Ethylenediamine	60.1	∞	1,000	893	0.021	10.7
Diethylenetriamine	103.2	∞	1,000	706	0.062	29.4
Monethanolamine	61.1	∞	1,012	939	0.015	7.2
Diethanolamine	105.1	95.4	996	722	0.057	27.5
Triethanolamine	149.1	∞	1,000	670	0.067	33.0
Monoisopropanolamine	75.1	∞	1,000	800	0.040	20.0
Disopropanolamine	133.2	87	1,000	543	0.091	45.7
Pyridines and Morpholines						
Pyridine	79.1	∞	1,000	527	0.095	47.3
2-Methyl 5-ethyl pyridine	121.2	sl.sol	1,000	107	0.179	89.3
n-Methyl morpholine	101.2	∞	1,000	575	0.085	42.5
n-Ethylmorpholine	115.2	∞	1,000	467	0.107	53.3
Aromatics						
Benzene	78.1	0.07	416	21	0.080	95.0
Toluene	92.1	0.047	317	66	0.050	79.2
Ethyl benzene	106.2	0.02	115	18	0.019	84.3
Phenol	94	6.7	1,000	194	0.161	80.6
Hydroquinone	110.1	6.0	1,000	167	0.167	83.3
Aniline	93.1	3.4	1,000	251	0.150	74.9
Styrene	104.2	0.03	180	18	0.028	88.8
Nitrobenzene	123.1	0.19	1,023	44	0.196	95.6
Esters						
Methyl acetate	74.1	31.9	1,030	760	0.054	26.2
Ethyl acetate	88.1	8.7	1,000	495	0.100	50.5
Propyl acetate	102.1	2	1,000	248	0.149	75.2
Butyl acetate	116.2	0.068	1,000	154	0.169	84.6
Primary amyl acetate	130.2	0.2	985	119	0.175	88.0

(Continued)

TABLE 3. (CONTINUED)

Compound	Molecular Weight	Aqueous Solubility (%)	Concentration (mg/liter)		Adsorbability	
			Initial	Final	g of Compound/ g of Carbon	Reduction (%)
Esters						
Isopropyl acetate	102.1	2.9	1,000	319	0.137	68.1
Isobutyl acetate	116.2	0.63	1,000	180	0.164	82.0
Vinyl acetate	86.1	2.8	1,000	357	0.129	64.3
Ethylene glycol monoethyl ether acetate	132.2	22.9	1,000	342	0.132	65.8
Ethyl acrylate	100.1	2.0	1,015	226	0.157	77.7
Butyl acrylate	128.2	0.2	1,000	43	0.193	95.9
Ethers						
Isopropyl ether	102.2	1.2	1,023	203	0.162	80.0
Butyl ether	130.2	0.03	197	nil	0.039	100.0
Dichloroisopropyl ether	171.1	0.17	1,008	nil	0.200	100.0
Glycols and Glycol Ethers						
Ethylene glycol	62.1	∞	1,000	932	0.0136	6.8
Diethylene glycol	106.1	∞	1,000	738	0.053	26.2
Triethylene glycol	150.2	∞	1,000	477	0.105	52.3
Tetraethylene glycol	194.2	∞	1,000	419	0.116	58.1
Propylene glycol	76.1	∞	1,000	884	0.024	11.6
Dipropylene glycol	134.2	∞	1,000	835	0.033	16.5
Hexylene glycol	118.2	∞	1,000	386	0.122	61.4
Ethylene glycol monomethyl ether	76.1	∞	1,024	886	0.028	13.5
Ethylene glycol monoethyl ether	90.1	∞	1,022	705	0.063	31.0
Ethylene glycol monobutyl ether	118.2	∞	1,000	441	0.112	55.9
Ethylene glycol monohexyl ether	146.2	0.99	975	126	0.170	87.1
Diethylene glycol monoethyl ether	134.2	∞	1,010	570	0.087	43.6
Diethylene glycol monobutyl ether	162.2	∞	1,000	173	0.166	82.7
Ethoxytriglycol	178.2	∞	1,000	303	0.139	69.7
Halogenated						
Ethylene dichloride	99.0	0.81	1,000	189	0.163	81.1
Propylene dichloride	113.0	0.30	1,000	71	0.183	92.9
Ketones						
Acetone	58.1	∞	1,000	782	0.043	21.8
Methyl ethyl ketone	72.1	26.8	1,000	532	0.094	46.8
Methyl propyl ketone	86.1	4.3	1,000	305	0.139	69.5
Methyl butyl ketone	100.2	v.sl.sol.	988	191	0.159	80.7
Methyl isobutyl ketone	100.2	1.9	1,000	152	0.169	84.8
Methyl isoamyl ketone	114.2	0.54	986	146	0.169	85.2
Diisobutyl ketone	142.2	0.05	300	nil	0.060	100.0
Cyclohexanone	98.2	2.5	1,000	332	0.134	66.8
Acetophenone	120.1	0.55	1,000	28	0.194	97.2
Isophorone	138.2	1.2	1,000	34	0.193	96.6
Organic Acids						
Formic acid	46.0	∞	1,000	765	0.047	23.5
Acetic acid	60.1	∞	1,000	760	0.048	24.0
Propionic acid	74.1	∞	1,000	674	0.065	32.6
Butyric acid	88.1	∞	1,000	405	0.119	59.5
Valeric acid	102.2	2.4	1,000	203	0.159	79.7
Caproic acid	116.2	1.1	1,000	30	0.194	97.0
Acrylic acid	72.1	∞	1,000	355	0.129	64.5
Benzoic acid	122.1	0.29	1,000	89	0.183	91.1
Oxides						
Propylene oxide	58.1	40.5	1,000	739	0.052	26.1
Styrene oxide	120.2	0.3	1,000	47	0.190	95.3

[a]Adapted from ref 108 by permission of the publishers.

TABLE 4. RELATIVE AMENABILITY TO CARBON ADSORPTION OF TYPICAL PETROCHEMICAL WASTEWATER CONSTITUENTS[a]

Initial compound concentration = 1000 mg/liter
Powdered carbon dosage = 5000 mg/liter

Compound	Adsorption (%)		Adsorption (%)
Ethanol	10	Vinyl acetate	64
Isopropanol	13	Ethyl acrylate	78
Acetaldehyde	12	Ethylene glycol	7
Butyraldehyde	53	Propylene glycol	12
Di-N-propylamine	80	Propylene oxide	26
Monoethanolamine	7	Acetone	22
Pyridine	47	Methyl ethyl ketone	47
2-Methyl 5-ethyl pyridine	89	Methyl isobutyl ketone	85
Benzene	95	Acetic acid	24
Phenol	81	Proprionic acid	33
Nitrobenzene	96	Benzoic acid	91
Ethyl acetate	50		

[a]From ref 107.

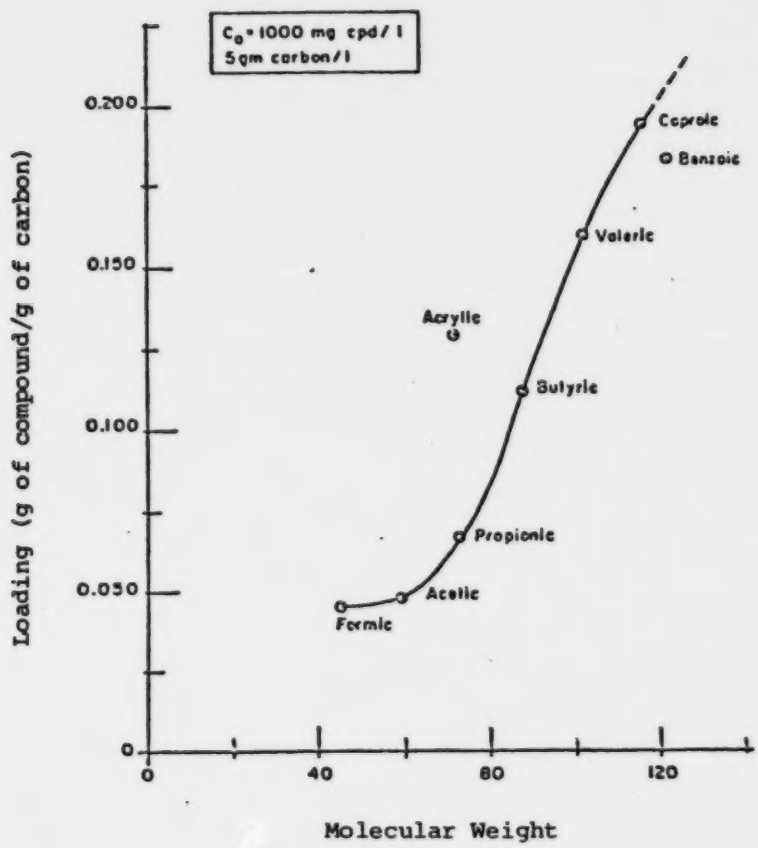


Figure 4. Effect of molecular weight on amenability of adsorption of organic acids (adapted from ref 84)

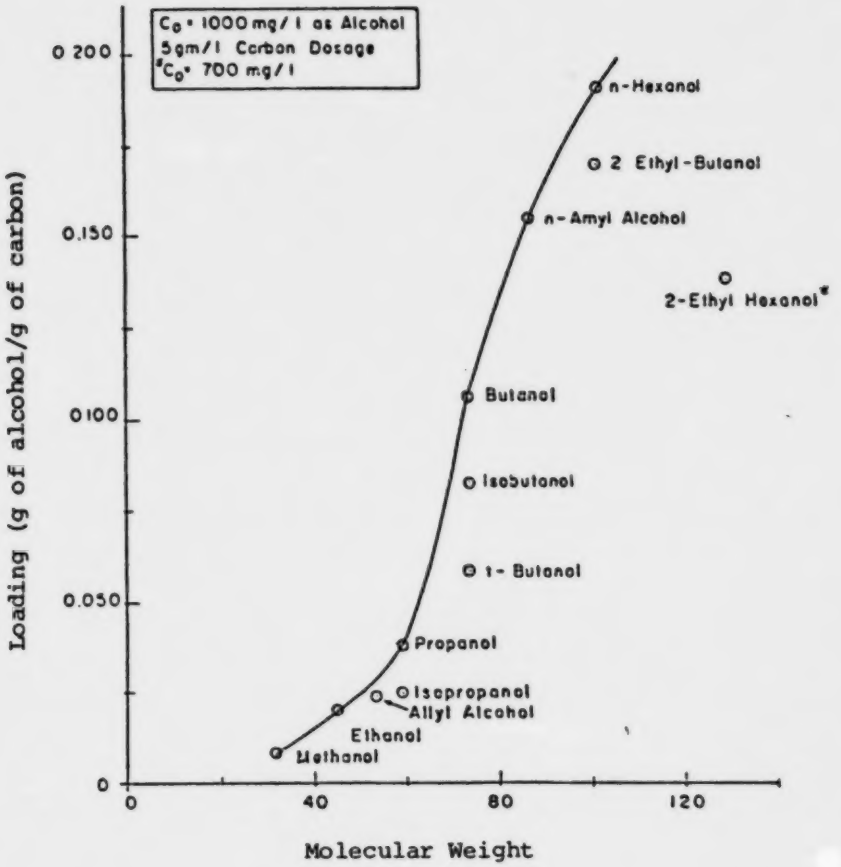


Figure 5. Effect of molecular weight on amenability of adsorption of alcohols (adapted from ref 84)

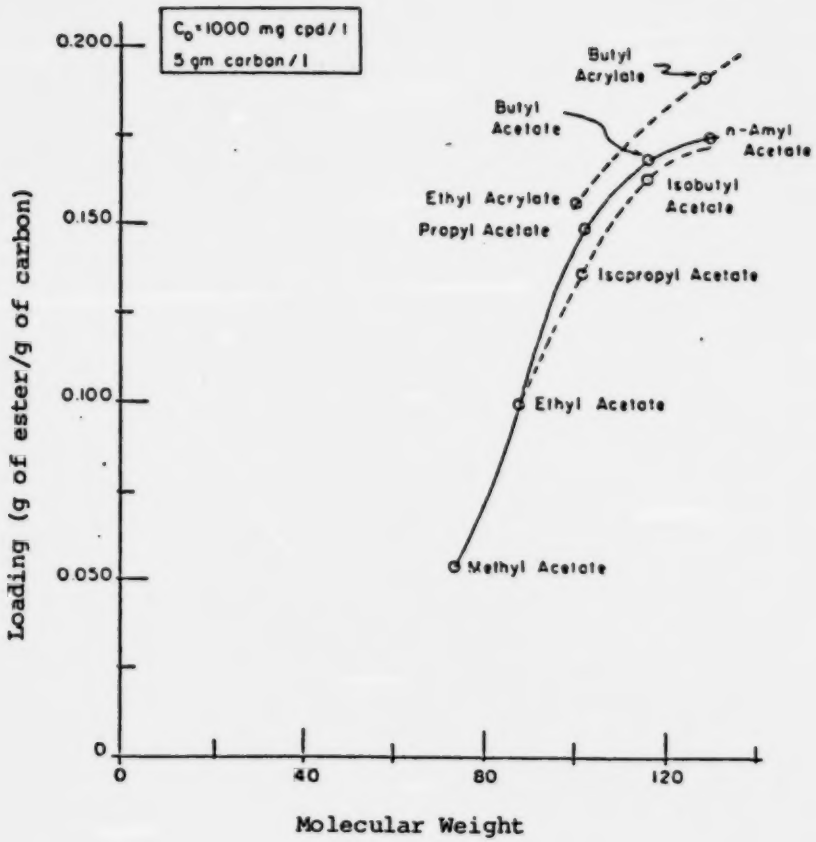


Figure 6. Effect of molecular weight on amenability of adsorption of esters (adapted from ref 84)

TABLE 5. INFLUENCE OF SUBSTITUENT GROUPS ON ADSORBABILITY[a]

Substituent Group	Nature of Influence
Hydroxyl	Generally reduces adsorbability; extent of decrease depends on structure of host molecule
Amino	Effect similar to that of hydroxyl but somewhat greater; many amino acids are not adsorbed to any appreciable extent
Carbonyl	Effect varies according to host molecule; glyoxylic is more adsorbable than acetic but similar increase does not occur when introduced into higher fatty acids
Double bonds	Variable effect as with carbonyl
Halogens	Variable effect
Sulfonic	Usually decreases adsorbability
Nitro	Often increases adsorbability
Aromatic rings	Greatly increases adsorbability

[a]From ref 107.

E. MULTIPLE COMPONENTS

The presence of multiple solutes in solution may change the equilibrium loading of a specific component when compared to pure-solute equilibrium data. The effects of competitive adsorption on individual-component loadings have been extensively documented in the literature (101, 105, 107, 108, 112, 113, 115, 117, 118). Multisolute isotherm data are compared with single-component data in Table 6.

F. ISOTHERM SURVEYS OF SPECIFIC COMPOUNDS AND INDUSTRIAL WASTEWATERS

The first step in evaluating the feasibility of treating a wastewater by adsorption has traditionally been to conduct isotherm tests. Although a number of studies in the literature (100, 103, 116, 119, 121, 123, 124) describe adsorption isotherms for various compounds, the variation in experimental techniques and methods of reporting the data makes it difficult to obtain meaningful comparisons of the adsorbability of different compounds. However, the EPA has conducted (103) a recent study in which adsorption isotherm data were collected for a large number of organic compounds.

A comprehensive survey of isotherms for industrial wastewater has been collected by a carbon vendor (109). Amenability to adsorption is expressed as a percent organic reduction, as measured by TOC. Results of this survey for SIC (Standard Industrial Classification, U.S. Department of Commerce) group 2818 (organic chemicals) are given in Table 7. It can be noted that, although carbon adsorption can yield very high degrees of organic reduction, in some cases massive amounts of carbon may be required to yield such removals.

TABLE 6. COMPARISON OF MULTICOMPONENT ISOTHERM DATA WITH SINGLE-COMPONENT DATA[a]

Compound	Equilibrium Carbon Loading in Mixture Test[b] (g of compound/g of carbon)	Equilibrium Carbon Loading in Single-Component Tests[c] (g of compound/g of carbon)	Fraction of Single-Component Equilibrium Loading from Mixture[d]
Mixture 1—Carbon A			
Butanol	0.116	0.110	1.05
Ethyl acetate	0.121	0.160	0.76
	0.237	0.270	
Mixture 2—Carbon A			
Methyl ethyl ketone	0.063	0.105	0.60
Butraldehyde	0.212	0.165	1.28
	0.275	0.270	
Mixture 3—Carbon A			
Butraldehyde	0.072	0.165	0.44
Ethyl acetate	0.075	0.160	0.47
Butanol	0.031	0.110	0.28
Butyric acid	0.112	0.140	0.80
	0.290	0.575	
Mixture 3—Carbon C			
Butyraldehyde	0.072	0.080	0.90
Ethyl acetate	0.066	0.080	0.83
Butanol	0.023	0.068	0.34
Butyric acid	0.064	0.084	0.76
	0.225	0.312	

[a]From ref 108. [b]Compounds each initially present at 500 mg/liter. Mixtures 1 and 3 dosed at 1 g of carbon/liter and mixture 2 at 2 g of carbon/liter. Equilibrium loadings are calculated from total TOC loadings and chromatographically determined fractional compositions of removed material. [c]Equilibrium loadings measured at an initial concentration of 500 mg/liter. [d]Calculated by dividing the equilibrium loading of the individual components in the mixture by the single component equilibrium loading.

TABLE 7. ADSORPTION ISOTHERM SURVEY OF SIC-2818, INDUSTRIAL ORGANIC CHEMICALS (FROM DATA IN REF 108)

Sample No.	Untreated Wastewater				Treated Water Organic Residual (mg/liter)		Organic Reduction (%)	Carbon Exhaustion Rate (lb/1000 gal)
	Suspended Solids (mg/liter)	pH	Parameter Test	Concentration (mg/liter)	Following Filtration	Following Adsorption		
81		7.0	TOC	8450	8100	2000	76	96
		7.0	Phenol		0.520	0.050	99	6.6
82	5	12.3	TOC	4850	4750	1300	73	493
		12.3	Phenol	0.12	0.12	0.003	99	2.6
83	325	6.7	TOC	136	37	13	91	10
84	5	11.1	TOC	1510	1400	465	70	86
85	5	11.6	TOC	2950	2600	12	99	103
86		4.0	TOC	8150	7750	5200	47	1496
		10.0			7750	5200	47	1496
87	444	4.3	TOC	8150	7800	5500	33	432
88	32	5.7	TOC	180	148	72	60	8.1
89	5	8.8	TOC	4900	4500	1000	80	374
	5	8.8	Phenol	0.315	0.313	0.001	99	12
90	50	5.2	TOC	4000	3525	145	96	81
91	100	6.6	TOC	3600	3250	60	98	110
92	135	9.4	TOC	4950	2400	95	98	64
93	135	9.4	TOC	4950	3700	18	99	118
94	5	2.0	TOC	410	370	16	96	9.6
95		8.5	TOC	15000	10500	8	99	311
96	34	9.3	TOC	9520	9250	20	99	213
97	30	10.5	TOC	12200	12200	11	99	389
98	30	10.6	TOC	13800	12700	70	99	293
99	110	9.7	TOC	245	200	28	89	17
	110	7.0	TOC	245	200	27	89	8.7
	95	8.2	TOC	230	170	4	98	8.9
100	20	7.3	TOC	3025	2940	120	96	163
101		0.1	TOC	430		175	60	436
	35	3.3	Phenol	12.8	11.3	0.001	99	7.7
102	35	3.3	TOC	280	240	13	96	6.0
	35	7.0	TOC	280	240	13	96	6.0
103		4.5	TOC	880	820	15	98	80
104		5.8	TOC	2350	2220	55	98	72
		4.0	TOC	2350	1920	60	98	94
		7.0	TOC	2350	2070	40	99	84
105		12.3	TOC	430	425	69	84	22
106	2420	8.3	TOC	2060	415	18	99	16
107		5.3	TOC	845	720	170	80	26
		5.3						
108	10	6.4	TOC	620	610	200	68	48
109	70	4.3	TOC	34	28	1	97	12
110	30	6.6	TOC	25	17	3.0	88	0.40

VII. DISCUSSION OF GRANULAR-ACTIVATED-CARBON PILOT-PLANT AND BENCH-SCALE DATA

A. COMPARISON OF CARBON LOADINGS OBTAINED IN ISOTHERM AND COLUMN TESTS

Unfortunately, the inherent adsorbability of a compound as measured by an isotherm test does not necessarily predict its degree of removal from a dynamic, continuous-flow system. The data in Table 8 clearly illustrate that adsorptive capacities calculated from isotherm studies may be significantly higher than capacities achieved in columns that are loaded to exhaustion. Nonideal flow conditions and limited contact times employed in column operation may play an important role in reducing column loadings to values less than those predicted from isotherm testing. Although the relative treatability of a particular wastewater by activated carbon may be estimated from isotherm data, it is imperative that carbon performance, column design characteristics, and cost effectiveness be defined by carbon-column pilot-plant testing.

B. INFORMATION OBTAINED FROM PILOT-TEST PROGRAMS

Information that must be evaluated during a pilot or laboratory carbon-adsorption testing program includes

1. breakthrough curve characteristics,
2. removal efficiency for specific components,
3. carbon working capacity,
4. carbon exhaustion rate,
5. multiple-solute effects,
6. bed depth,
7. contact time.

Evaluation of any one of these factors by itself is of limited usefulness. Therefore in any interpretation of pilot or laboratory test data both the characteristics of the wastewater stream and the mode in which the wastewater is contacted with the carbon must be taken into account. Column tests are frequently run under unrealistic operating conditions. For example, small-diameter columns, short bed depths, unrealistic contact times, and unrepresentative wastewater feeds are common shortcomings of data collected during pilot or laboratory carbon-adsorption studies.

The essential operating parameters measured during numerous column studies are given in Appendix A. The data tabulated include flow, pretreatment, number and

TABLE 8. COMPARISON OF ACTIVATED-CARBON CAPACITY IN ISOTHERM TEST VS CAPACITY IN COLUMN TEST

Wastewater Composition	Capacity (g/g)		Data Source[a]
	Isotherm	Column at Exhaustion	
Petrochemical plant biotreated effluent (as COD)	0.650	0.24	83
Petrochemical plant biotreated effluent (as COD)	1.300	0.26	83
Petrochemical plant raw wastewater (as COD)	0.075	0.05	83
1,2-Dichloroethane	0.208	0.17	76
1,2-Dichloroethane	0.910	0.44	67
Methyl ethyl ketone	0.160	0.13	84
Butyraldehyde	0.220	0.19	84
4-Component mixture (as TOC)	0.170	0.15	84
Refinery effluent (as COD)	1.750	0.30	107

[a]See Section X.

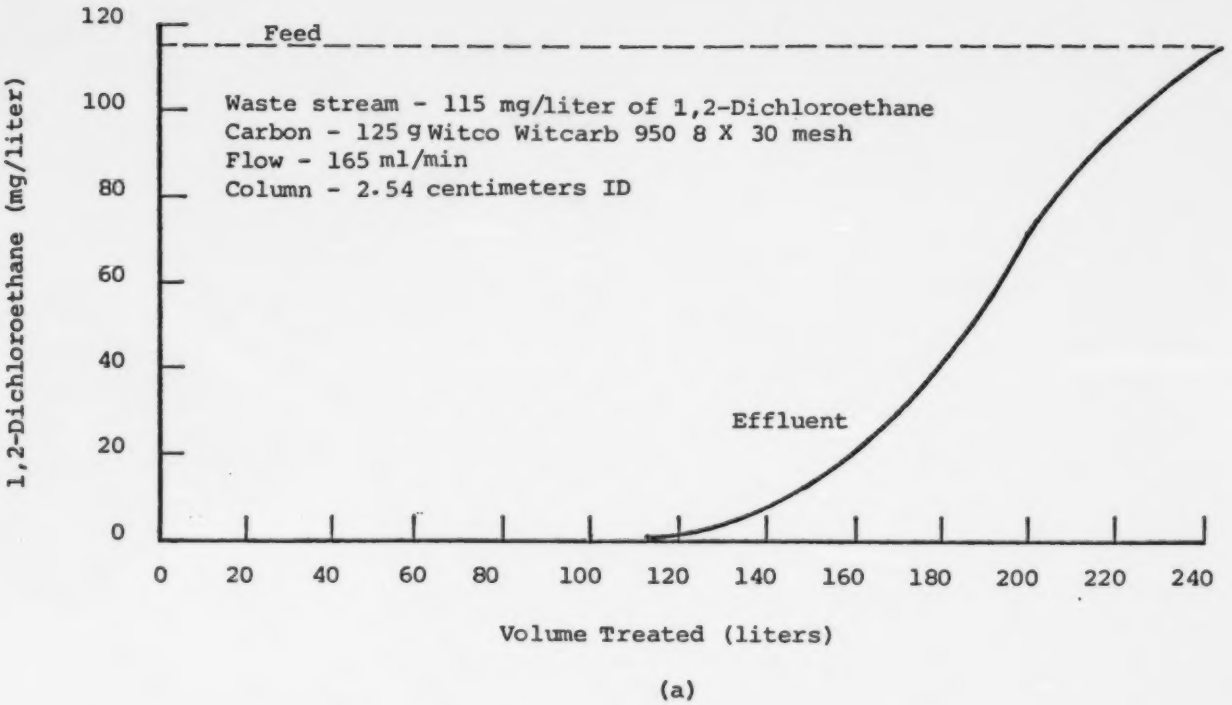
size of adsorbers, hydraulic loading rate, contact time, type of carbon, total carbon inventory in columns, carbon exhaustion rate, and pollutant removal data. Treatment performance data reported in the literature are either the average of composite samples up to breakthrough or are an arbitrarily defined breakthrough concentration. Since contaminant removal efficiency, carbon exhaustion rate, and carbon loading capacity are interrelated, the method used in reporting effluent data is critical for an evaluation of the use of carbon adsorption as a viable treatment technology. Effluent data in Appendix A are denoted as either an average value or the value at breakthrough.

C. RELATIONSHIP BETWEEN REMOVAL EFFICIENCY, LOADING, AND CARBON EXHAUSTION RATE

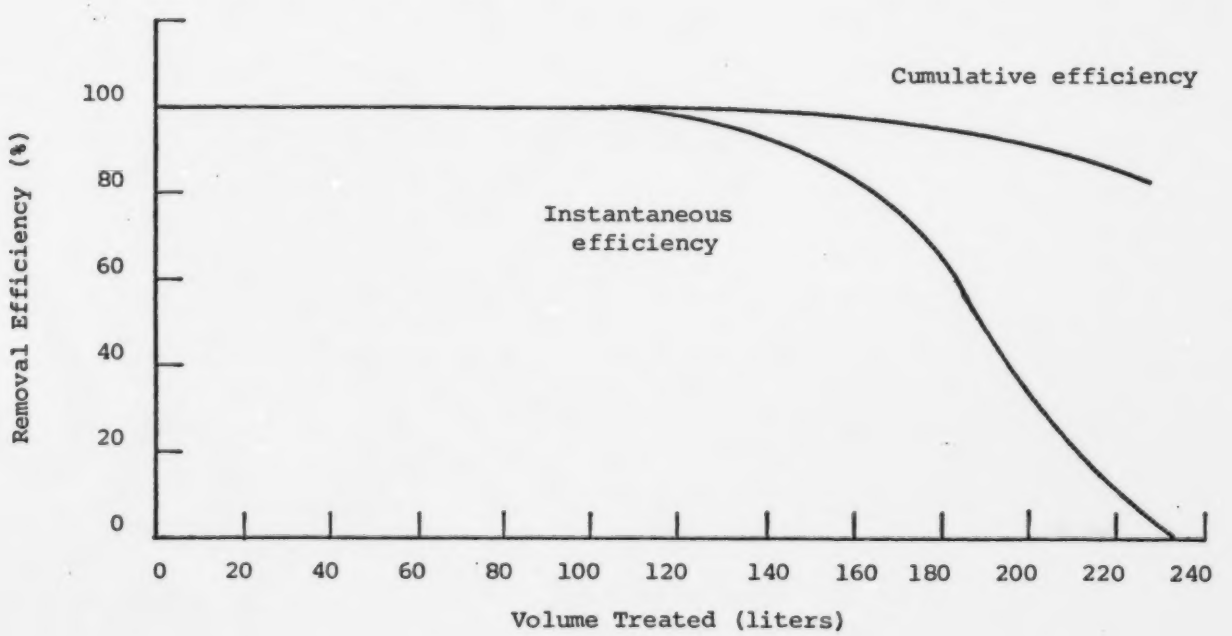
The carbon exhaustion rate may be defined as the weight of carbon required for treating a specified volume of wastewater to a specific effluent quality. Obviously, the carbon exhaustion rate is a function of the type and concentration of the solute, as well as of the effluent concentration requirements. The carbon exhaustion rate approaches an infinite value as the bed service time per adsorption cycle approaches zero. Although a component may be efficiently removed from a wastewater stream, short bed service times and excessive regeneration costs may preclude the use of carbon adsorption as an appropriate treatment technology.

Figures 7 and 8 demonstrate the relationship between the volume of wastewater treated per cycle and the efficiency, loading, and carbon exhaustion rate. The efficiency at breakthrough is the percentage removal of the compound in question at the time that the column is taken off-stream for regeneration. Cumulative efficiency is the average percent removal of the solute from the time that the column is placed on-stream to the time that the column is taken off-stream for regeneration. As the effluent concentration approaches the feed concentration, the instantaneous efficiency at breakthrough approaches zero. However, as is illustrated in Fig. 7(b), the cumulative removal efficiency since the time that the column was placed on-stream may still be quite high.

Pilot carbon columns are typically removed from service when the effluent concentration reaches a predetermined value. For the example in Fig. 7(a), breakthrough occurs after treatment of approximately 120 liters of wastewater. Figure 8(a) shows that the 1,2-dichloroethane loading on the carbon at break-

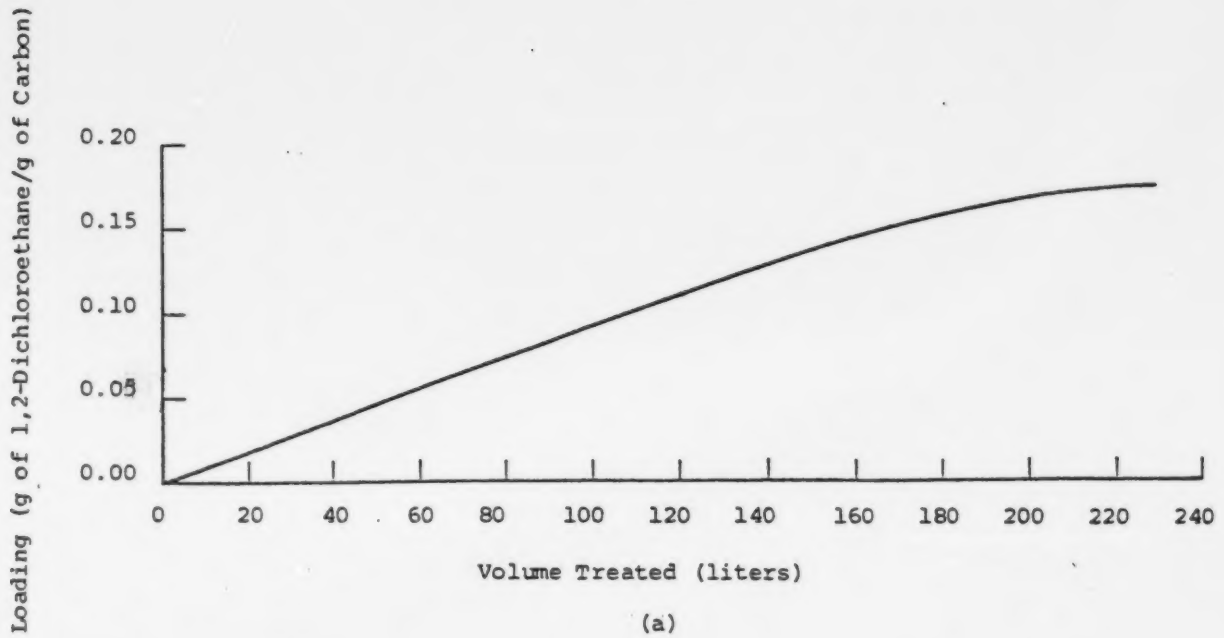


(a)

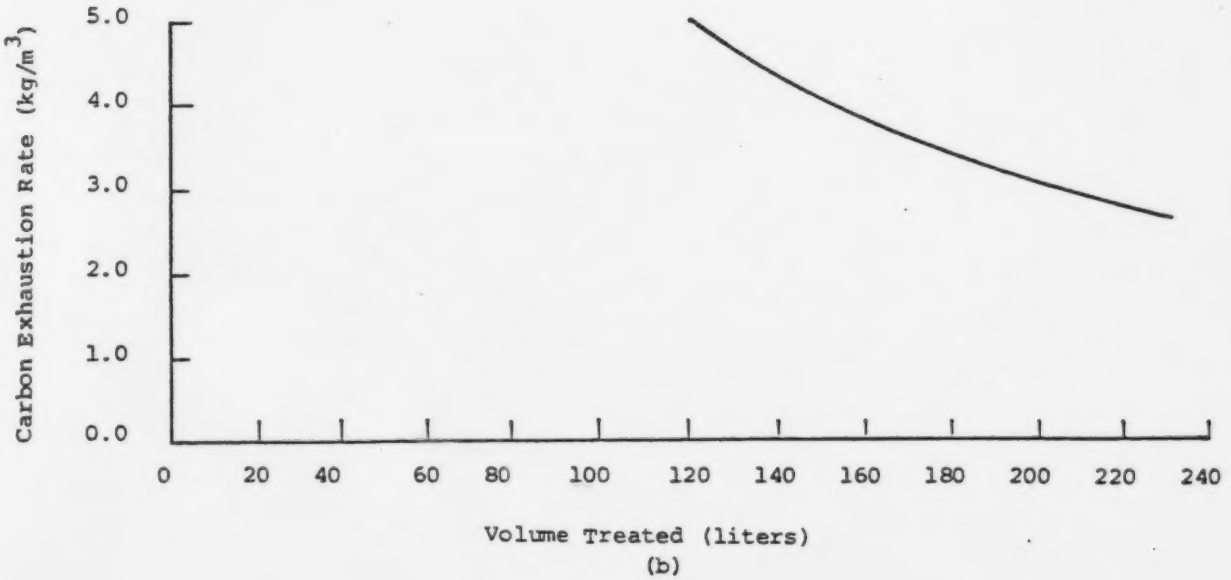


(b)

Figure 7. Evaluation of bench-scale carbon column data.
(a) Breakthrough curve. (b) Removal efficiency.
(from ref 76)



(a)



(b)

Figure 8. Evaluation of bench-scale carbon column data.

(a) Loading vs throughput. (b) Carbon exhaustion rate vs throughput. (from ref 76)

through is approximately 0.11 g/g. However, the carbon still has considerable capacity left. Figures 7(a) and 8(a) show that the carbon has an ultimate capacity of 0.17 g/g before the column is completely exhausted.

Figure 8(b) illustrates that, if the column described in Fig. 7(a) is taken off-line at breakthrough, a carbon exhaustion rate of 5.0 kg of carbon/m^3 of wastewater will result. When, however, the column is loaded to exhaustion, the carbon exhaustion rate for this example is reduced to approximately 2.6 kg/m^3.

D. BREAKTHROUGH-CURVE CHARACTERISTICS

The adsorption zone of a carbon column may be defined as the region of the column in which the concentration of contaminants in the wastewater stream is reduced from the influent value to some lower limiting concentration. As the carbon becomes saturated, the zone of adsorption moves in the direction of the flow, until the zone reaches the outlet point of the column. The length of the adsorption zone has been shown to be a function of the properties of the solute, the properties of the activated carbon, and the linear flow velocity through the column (98).

If the adsorption zone is long, a broad breakthrough curve will result, which may be indicative of slow kinetics of adsorption. A system exhibiting rapid kinetic reactions will yield a short breakthrough curve in which the concentration of solute in the effluent will quickly rise to equal the concentration in the column feed.

E. BED DEPTH

An evaluation of carbon column efficiency obtained by treating a volume of wastewater at an arbitrarily defined breakthrough concentration is of limited usefulness in terms of design of large columns. If a column is taken off-line at an arbitrarily defined breakpoint, a significant amount of the adsorptive capacity of the column may be unused. The degree to which the adsorptive capacity of the column is not utilized is a function of both the depth of the adsorption zone and the length of the column.

The data in Table 9 illustrate the increase in loading of sodium nitrophenol as a function of bed depth at a specified breakthrough effluent concentration. This apparent increase in loading as a function of bed depth is due to the

TABLE 9. ACTIVATED-CARBON LOADING OF SODIUM NITROPHENOL (SNP) AS A FUNCTION OF BED DEPTH[a]

Column Performance	Bed Depth (ft) 5	10	15	20
Run 1				
Influent SNP concentration, 2000 mg/liter				
Effluent SNP concentration, 5 mg/liter				
Hydraulic loading rate, 41.2 ml/min (0.5 gpm/ft^2)				
Service time (hr)	22	58	90	140
Carbon (g)	1357	2795	4187	5587
SNP adsorbed (g)	108.8	286.8	445.0	692.2
Loading (g of SNP/g of carbon)	0.080	0.103	0.106	0.124
Carbon exhaustion rate (kg/m^3)	121	94	91	78
(lb/1000 gal)	208	162	157	134
Run 2				
Influent SNP concentration, 2000 mg/liter				
Effluent SNP concentration, 5 mg/liter				
Hydraulic loading rate, 148 ml/min (1.8 gpm/ft^2)				
Service time (hr)	3.5	10.8	20	28
SNP adsorbed (g)	62.2	191.8	355.2	497.3
Loading (g of SNP/g of carbon)	0.046	0.069	0.085	0.089
Carbon exhaustion rate (kg/m^3)	211	141	114	109
(lb/1000 gal)	364	243	196	187
Run 3				
Influent SNP concentration, 2200 mg/liter				
Effluent SNP concentration, 5 mg/liter				
Hydraulic loading rate, 341 ml/min (4.14 gpm/ft^2)				
Service time (hr)	0.3	2.5	5.25	7.5
SNP adsorbed (g)	12.3	102.3	214.8	337.6
Loading (g of SNP/g of carbon)	0.009	0.037	0.051	0.060
Carbon exhaustion rate (kg/m^3)	1071	265	189	176
(lb/1000 gal)	1843	456	325	303

[a]Adapted from Tables 2 and 3, p. 46, of ref 93 by permission of the publisher.

exhaustion of the upper bed layers as the adsorption zone moves through the column.

An increase in loading with an increase in bed length, up to an equilibrium value, is normal for an activated-carbon column treating a single-solute wastewater stream. However, these results cannot be extrapolated to a system treating a multicomponent wastewater stream, especially if the performance is reported in terms of a gross parameter, such as BOD_5, COD, or TOC. From the breakthrough curves in Figure 9, it is seen that column 2 provides some incremental degree of COD removal. Lawson and Fisher (83) hypothesize that the first column removes those components of the total wastewater COD that are readily amenable to adsorption, leaving a feed for the second column that predominantly contains species that are resistant to adsorption. The dilute amenable species remaining after column 1 are essentially the only species adsorbed in column 2, hence a low absolute COD removal in the second column as far as jthe run was conducted. Loadings for the second column of a 2-column series configuration were found to vary from 57 to 65% of the loadings obtained on the lead column when treating a petrochemical waste (84).

F. CONTACT TIME

Although contact time has been recognized as a critical design parameter (104), only in a few of the pilot- and bench-scale studies examined was an attempt made to optimize contact time. A study by Perrotti (88) included evaluation of treatment of phenolic paint waste stripping wastewater at contact times of 15, 30, 45, and 60 min. However, variations in the influent wastewater concentration preclude any comparison being made between column performance at varying contact times.

G. MULTIPLE-SOLUTION INTERACTIONS

Several researchers have demonstrated that multiple-solute interactions can lead to sequential adsorption/desorption and chromatographic separations in activated carbon columns (77, 82, 102, 106, 118, 120). Figure 10(a) illustrates such a separati on for a binary-component (1,2-dichloroethane and toluene) mixture. The 1,2-dichloroethane component breaks through after treatment of 20 liters of wastewater. A portion of the 1,2dichloroethane that was adsorbed is then

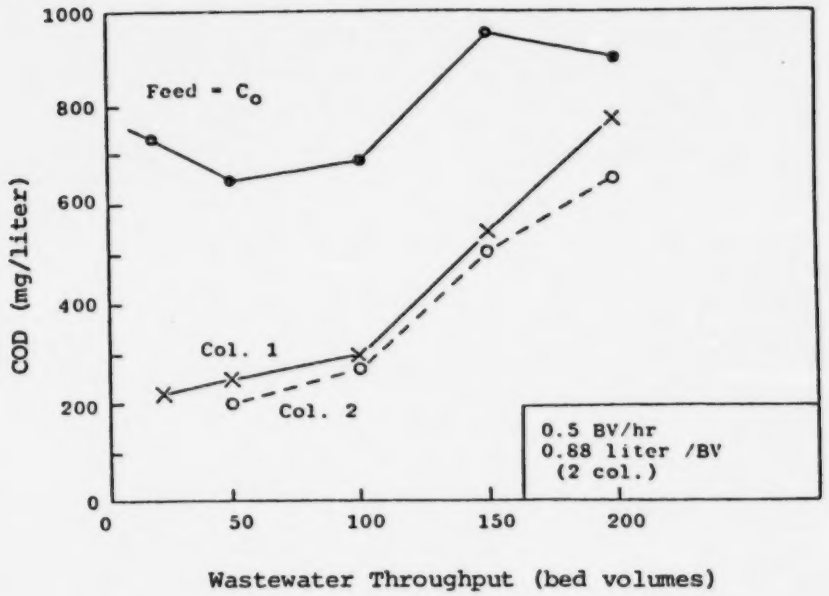
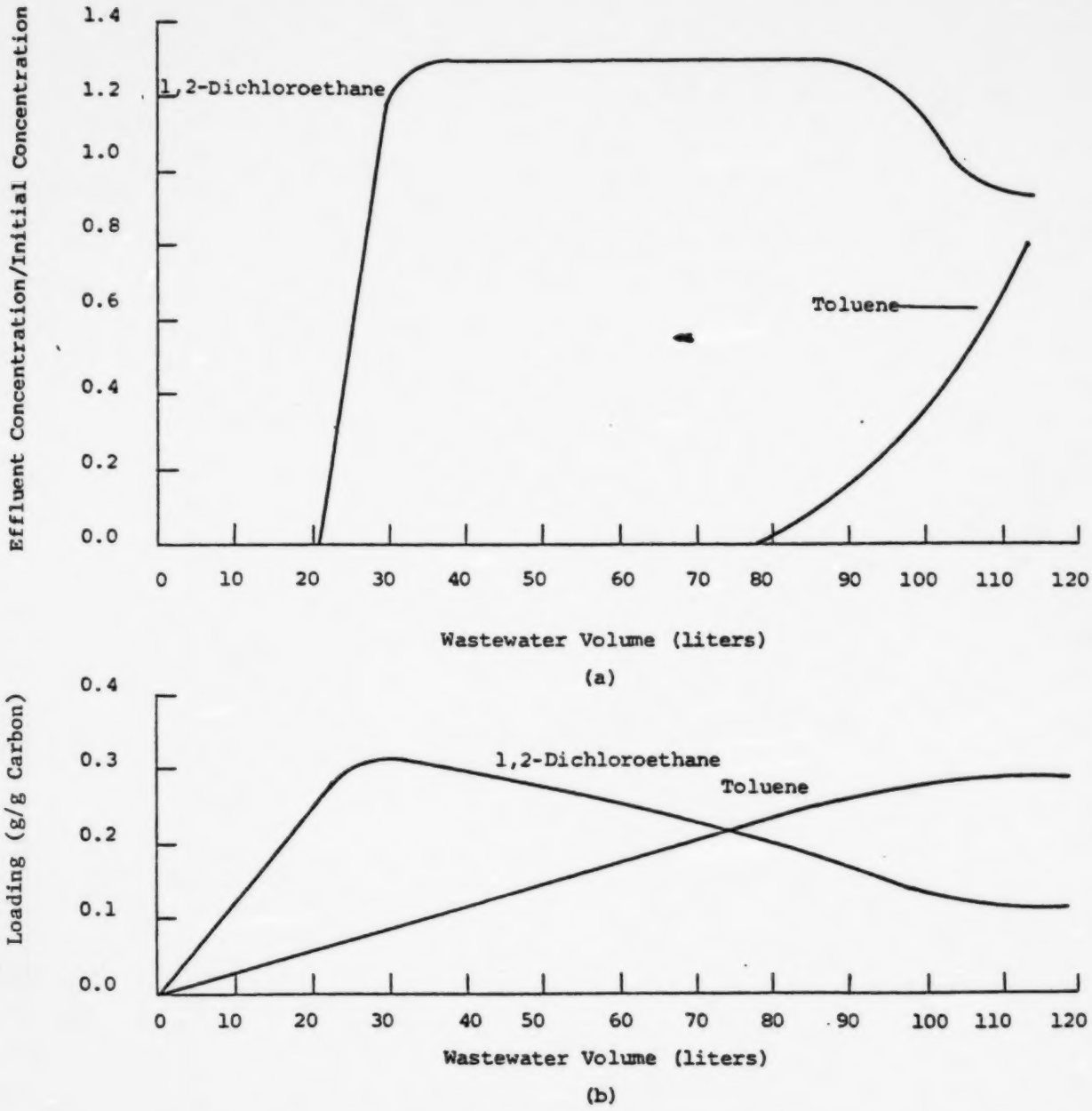


Figure 9. Breakthrough curve for bio-treated wastewater (adapted from ref 83 by permission of the author)



Test Conditions: Carbon, 125 g of Witco Witcarb 950 8 X 30 mesh; column, 2.54 cm ID; flow, 80 ml/min; pH, 7; 1,2-Dichloroethane feed concentration, 1468 mg/liter; toluene feed concentration, 331 mg/liter

Fig. 10. Binary component adsorption data. (a) Breakthrough curves. (b) Loading. (from ref 77)

eluted from the column as toluene is preferentially adsorbed. The concentration of 1,2-dichloroethane in the effluent reaches a plateau at a value of approximately 1.3 times the influent concentration. During this period the mass loading rate of toluene is appoximately equal to the rate at which 1,2-dichloroethane is being desorbed. Figure 10(b) shows that as the carbon column nears exhaustion the loadings of toluene and of 1,2-dichloroethane reach equilibrium values. The carbon column capacity (at exhaustion) is compared with single-solute isotherm data in Table 10.

TABLE 10. COMPARISON OF SINGLE-SOLUTE ISOTHERM LOADING WITH BINARY-COMPONENT COLUMN LOADING

	Adsorptive capacity (g/g of carbon)		
Component	Single-solute isotherm	Column at exhaustion	Column at breakthrough
1,2-Dichloroethane	0.57	0.12	0.26
Toluene	0.40	0.29	0.24

Although several adsorption models have been developed for binary-solute systems (102, 106, 116, 118), none have been shown to be applicable to complex, multicomponent mixtures. The degree to which a component may be removed from a multicomponent wastewater stream must be established by pilot-plant testing for each individual wastewater stream. Although activated-carbon adsorption may prove to be highly efficient for removal of a specific component from a given wastewater stream, it may be significantly less efficient for removing the same compound from a wastewater stream of different composition.

Similar results have been reported (82) for a multicomponent wastewater stream from a petrochemical plant. Three of the components in the wastewater stream were concentrated and eluted with peak concentration values 1.5 to 2.5 times higher than the concentrations in the column influent. Figure 11 (82) shows the breakthrough curves for the specific organic compounds. It can be noted that these desorption phenomena are not reflected in the COD breakthrough curve at the top of Fig. 11, because the most strongly adsorbed constituent (compound X) was present in by far the greatest initial concentration.

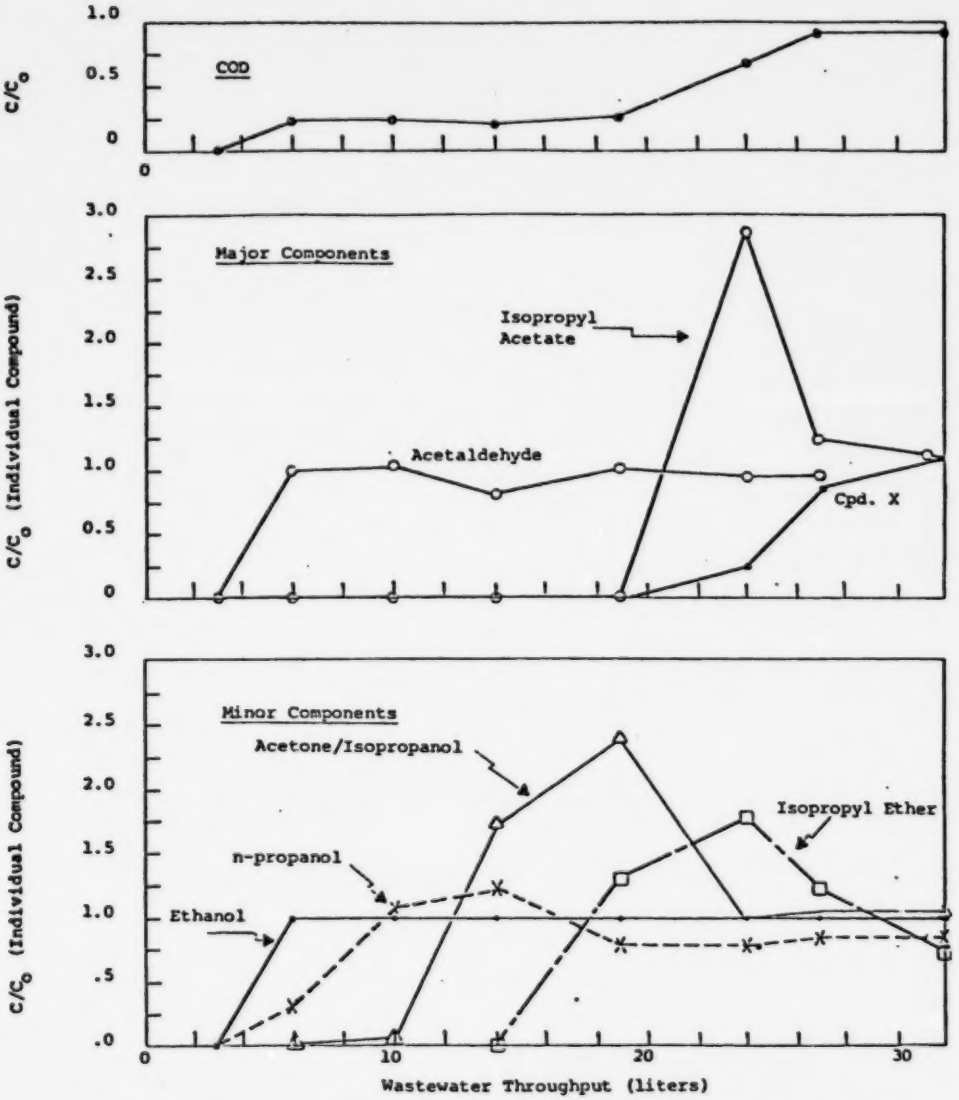


Figure 11. Breakthrough of components in mixture (from ref 82 by permission of the editor)

Initial Concentrations (C_o), mg/liter

Compound	Compound	Equivalent COD
Compound X	5950	8450
Acetaldehyde	1440	2620
Isopropyl Acetate	421	1220
Isopropyl Ether	77	220
Acetone/Isopropanol	60	140
n-Propanol	22	50
Ethanol	2	4
		12,704

Rate 1.2 l/hr
Bed Wt. - 400 g of carbon

H. ORGANIC REMOVAL EFFICIENCY

Table 11 contains a list of compounds that have been reported in studies (referenced in the table) involving pilot- or bench-scale evaluations of activated-carbon adsorption. Influent and effluent concentrations and carbon loading capacities are from the cited sources when that information was available. As shown by the data in Table 11, carbon adsorption can be a highly efficient unit process for the treatment of a wide variety of organic contaminants. However, care should be taken in interpreting these data since in many instances the data in Appendix A indicate that the system operating characteristics are not fully known.

TABLE 11. GRANULAR-ACTIVATED-CARBON ADSORPTION IN PILOT- AND BENCH-SCALE TESTS

Compound	Influent (mg/liter)	Effluent (mg/liter)	Loading (g/g of carbon)	Single-Component Stream	Multicomponent Stream	Data Source
Acetaldehyde	1440	144	< 0.01		x	82
Carbon tetrachloride					x	68
Chloroethane	45	63			x	87
	390	0			x	87
	110	0			x	87
	59	150			x	87
	150	190			x	87
	330	0			x	87
	0	240			x	87
	170	0			x	87
Chloroform	34	0			x	87
Dimethyl formide	1575	950			x	79
	1575	1000			x	79
1,1-Dichloroethane	59	4			x	87
	40	0			x	87
	79	0			x	87
	78	45			x	87
	45	8			x	87
	310	0			x	87
	190	0			x	87
1,2-Dichloroethane	7000	4	0.38		x	67
	7000	12	0.39		x	67
	7000	1	0.44		x	67
	120	10	0.13	x		76
	1000	190			x	87
	950	0			x	87
	920	0			x	87
	960	750			x	87
	760	130			x	87
	3000	0			x	87
					x	68
	3100	970	0.20		x	87
	1800	37	0.13		x	87
	2500	1100	0.16		x	87
	1700	100	0.27		x	87
	3700	0	0.33		x	87
Ethanol	2	0.2	<0.01		x	82
Isopropyl acetate	421	42	0.02		x	82
Isopropyl ether	77	7.7	<0.01		x	82
Methylenedianiline	62.6	10	0.05		x	97
	550	0	0.05		x	83
n-Propanol	22	2.2	<0.01		x	82
n-Nitrosodimethylamine	193	10	0.05	x		86
Phenol	3000	100	0.13	x		80
	3000	100	0.25	x		80
	4600	10	0.16	x		78
	4600	10	0.27	x		78
	1050	5			x	79
	1050	20	0.105		x	79
Sodium nitrophenol	2000	5	0.12		x	93
Trinitrotolyene	1000	1	0.20		x	71
	53.8	1	0.13		x	92
1,1,1,2-Tetrachlororethene					x	68
1,1,2,-Trichloroethane					x	68

VIII. DISCUSSION OF FULL-SCALE INDUSTRIAL APPLICATIONS OF GRANULAR-ACTIVATED-CARBON ADSORPTION

A. GENERAL

Information gathered from activated-carbon vendors indicates that more than 100 domestic granular-activated-carbon systems are being used for the treatment of industrial wastewaters. Information in this section is not restricted to organic chemical manufacturers, but also includes data from petroleum refineries and textile manufacturers. These data are included because many of the same contaminants present in wastewaters from these industries are typically found in wastewater streams from organic chemical plants.

Table 12 contains a list of installations reported to have had full-scale experience with this technology. The list is not comprehensive, since the use of activated-carbon adsorption is considered to be proprietary information by many firms. The information does, however, reflect material gathered from a wide variety of data sources, including carbon vendors, industrial users of activated carbon, the open literature, government documents, and state and EPA files.

Appendix B contains a comprehensive compilation of the data collected for the full-scale systems. In order to define the effectiveness of granular-activated-carbon treatment, a wide variety of data was sought including the following:

1. type and amount of contaminant removed
2. removal efficiency
3. wastewater flows
4. pretreatment requirements
5. number of columns
6. column dimensions
7. column configuration
8. hydraulic loading rate
9. contact time (system)
10. type of carbon
11. carbon inventory (in columns only)

TABLE 12. COMPANIES REPORTED TO HAVE EXPERIENCE WITH FULL-SCALE GRANULAR-ACTIVATED-CARBON SYSTEMS

Company	Location	Principal Product	Data Source
Alcolac	Sedalia, MO	Surface active agents	43
Allied Chemical	Fairfield, AL	Creosote oils, tars, pitches	12, 37
	South Point, OH	Formaldehyde	41
	Frankford, PA	Organic chemicals	41
	Buffalo, NY	Inorganic chemicals	41
	Syracuse, NY	Monochlorobenzene, o-dichlorobenzene	12
	Hopewell, VA	Organic chemicals	41
	Moundsville, WV	Toluene diisocyanate, methylene dianiline	63
Amerada Hess	a	Refinery products	24
American Aniline	a	b	24
American Color and Chemical	Lockhaven, PA	Dyes	12
American Cyanamid	Bound Brook, NJ	Organic chemicals	2, 14, 24, 35
Atlantic Richfield[c]	Carson, CA	Refinery products	24, 33, 39, 44, 45, 46, 54, 62
Atlantic Richfield/ Polymers, Inc.	Monaca, PA	Diethylebenzene, divinyl benzene	12
BASF Wyandotte	Geismar, LA	Chlorine, hydrogen, sodium hydroxide	59
	Washington, NJ	Polypropoxy ethers, polypropylene glycol	62
Beckman Instrument Co.	Porterville, CA	b	56
Borden, Inc.	Bainbridge, NY	Plastics and resins	12
British Petroleum Corp.[c]	Marcus Hook , PA	Refinery products	16, 36, 39, 45, 54
C.H. Masland	Wakefield, RI	Textiles	7, 62
Ciba Geigy	St. Gabriel, LA	Pesticides	59
Crompton and Knowles Corp.	Gibraltar, PA	Dyes	62
Diamond Shamrock	Houston, TX	Pesticides	60
Dow Chemical	Gales Ferry, CT	Plastics and resins	12
	Plaquemine, LA	Organic chemicals	41
	Midland, MI	Phenol, acetic acid	7, 12, 21, 27, 37, 45, 54
Du Pont			
	Beaumont, TX	Pharmaceutical chemicals	34, 41, 143
	Richmond, VA	Textile fibers	41, 143
	Belle, WV	Organic chemicals	41
EPA Emergency Response Unit	Mobile Unit	Chemical spill cleanup	5
Fike chemical	Nitro, WV	Specialty organic chemicals	63
First Chemical Corp.	Pascagoula, MS	Aniline, nitrobenzene, nitrotoluene	12, 34
FMC	Baltimore, MD	Pesticides	41
	So. Charleston, WV	Organic chemicals	41
	Nitro, WV	Organic chemicals	41
	Middleport, NY	Pesticides	41
	Bayport, TX	Plasticizers, glycerin	41
General Electric	Pittsfield, MA	Plastics and resins	37
	Fort Edwards, NY[d]		61
	Selkirk, NY	Plastics and resins	32, 37, 61, 62
Georgia Pacific	Conway, NC	Phenolic resins	46, 62
Hardewicke Chemical	Elgin, SC	Specialty organic chemicals	22, 32, 37, 55, 58
Hercules, Inc.	Hattiesburg, MS	Terpene oils, hydrocarbon resins	16, 23, 37, 38, 45, 54
Hooker	Hahnville, LA		12, 59
Houston Chem. Div. of PPG	Beaumont, TX	Ethylene glycol, ethylene dibromide	12

(Continued)

Table 12. (Continued)

Company	Location	Principal Product	Data Source
ICI Americas	Goldsboro, NC	Pesticide research	6
Iowa Army Ammunition Plant	Burlington, IA	Explosives	11, 25, 30, 62
Joliet Army Ammunition Plant	Joliet, IL	Explosives	11
Kansas Army Ammunition Plant	Parsons, KS	Explosives	11, 20
Liquified Coal Development Corp.	Captina, WV	Anthracene-derived solvents	63
Lone Star Army Ammunition Plant	Texarkana, TX	Explosives	20
Louisiana Army Ammunition Plant	Shreveport, LA	Explosives	20
Matlack	Swedesboro, NJ	Tank truck washing	14, 40, 54
Mobay	Cedar Bayou, TX	Organic chemicals	24, 62
	New Martinsville, WV	Isocyanates, polyols, polesters	24, 34, 63
Monsanto	Anniston, AL	Polynitrophenol	37
	Sauget, IL	Organic chemicals	41
	St. Louis, MO	Organic chemicals	41
	Alvin, Tx	Organic chemicals	41
	Texas City, Tx	Organic chemicals	41
	Luling, LA	Cyclohexanol	41
	Nitro, WV	Pesticides	41
Neville Chemical	Neville Island, PA	Plastics, resins	43,66
Olin Corp.	McIntosh, AL	Pesticides	41
	Bradenberg, KY	Organic chemicals	41
	Rochester, NY	Organic chemicals	41
	Ashtabula, OH	Organic chemicals	41
Owens Corning	Anderson, SC	Plastics and resins	55, 57, 58
Palisades Industries	Peace Dale, RI	Textiles	7, 45, 50, 54
Pennwalt	Houston, TX	Organic chemicals	12
Pfizer Chemical	Terrahaute, IN	Pharmaceutical chemicals	41
	South Port, NC	Citric acid	41
	Brooklyn, NY	Organic chemicals	41
	Greensboro, NC	Organic chemicals	41
	Sanford, NC[d]		41
Proctor and Gamble	Chicago, IL	Fatty acids	41
	Baltimore, MD	Fatty acids	41
	Kansas City, KS	Fatty acids, alcohols	41
	Dallas, Tx	Fatty acids	41
Reichhold Chemical	Tuscaloosa, AL	Phenol, pentaerythritol, resins	10, 37, 45, 51, 54, 62
Republic Steel	Cleveland, OH	Coke	24, 52
Rhodia (Rhone-Poulenc)	Freeport,[c] TX	Organic chemicals	60, 64
	Portland, OR	Pesticides	10, 26, 32, 37, 46, 62
Rocky Mountain Arsenal	Denver, CO	b	43
Rogers Corporation	Manchester, CT	Plastics and resins	12
SCA Chemical Waste Services	Lewiston, NY	Chemical waste disposal	61
Schenectady Chemical	Schenectady, NY	Phenolic resins	10, 37, 61, 62
Sherwin Williams Co.	Chicago, IL	Para-cresol	34, 37, 62
Stauffer Chemical	Bucks, AL[d]		41
	Lemoyne, AL	Sulfur	41
	Richmond, CA	Pesticides	41
	Dominquez, CA	Inorganic chemicals	41
	San Jose, CA	Flavor and fragrance chemicals	41
	Delaware City, DE	Carbon disulfide	41
	Louisville, KY	Organic chemicals	41
	Geismar, LA[d]		41
	Henderson, NV	Organic chemicals	41
	Skaneateles Falls, NY	Detergents	37, 41, 61, 62
	Galliopolis Ferry, WV	Synclubricants, plasticizers, esters	41, 63

(Continued)

Table 12. (Continued)

Company	Location	Principal Product	Data Source
Stauffer Chemical	Green River, WY[d]		41
Stepan Chemial	Fieldsboro, NJ	Detergent intermediates	9, 10, 24, 37, 62
Stephen-Leedom Carpet	Southampton, PA	Carpets	7, 19, 46, 62
Tooele Army Ammunition Plant	Tooele, UT	Explosives	11
TRA	Irving, TX	b	24
Union Carbide	Hahnville, LA[d]		41
	Ponce, PR[d]		41
	Greenville, SC	Synthetic fibers	41
	Woodbine, GA[d]		41
Velvet Textile Co.	Blackstone, VA	Textiles	19, 62
Vicksburg Chemical	Vicksburg, MS	Toxaphene, methyl parathion	37
Yorktown Naval Weapons Station	Yorktown, VA	Explosives	20
Unidentified (1)[e]		Pesticides	31
Unidentified (2)		Organic chemicals	10
Unidentified (3)		Explosives	17
Unidentified (4)		Chlorobenzene, dichlorobenzene	65
Unidentified (5)		Toxaphene, DNBP, cyanazine	18
Unidentified (6)		Dalpon	18
Unidentified (7)		2,4-D, 2,4-DB, MCPA	18
Unidentified (8)		Parachloronitrobenzene, terrazole	18
Unidentified (9)		Dicofol	18
Unidentified (10)		Trifluralin, isopropanol, ethalfluralin	18
Unidentified (11)		DEET, piperonyl butoxide, thanite	18
Unidentified (12)		Carbofuran	18
Unidentified (13)		Atrazine	18

[a]Location not given in data source.

[b]Information incomplete.

[c]Unit known to be shut down.

[d]No plant listed at this location in 1979 Directory of Chemical Producers.

[e]Neither company nor location identified in data source

12. carbon exhaustion rate
13. regeneration technique
14. carbon loss/regeneration cycle
15. utilities cost
16. operating cost
17. capital costs

Significant performance data were available for approximately 50 granular-carbon-adsorption units. A synopsis of these data, which consist of pertinent engineering design features, carbon performance and cost information, and performance characteristics for removal of conventional contaminants, is given in Tables 13, 14, and 15 respectively.

Due to widely varying characteristics in the wastewater streams being treated and the diverse designs of the adsorption systems, direct comparisons between performance for different installations are impractical. Therefore the data in Appendix B are discussed by data classification rather than by individual adsorption systems.

B. ORGANIC REMOVAL

Most industrial wastewater streams contain multiple compounds and typically exhibit time-variable compositions. Hence in most of the data available for full-scale systems effluent quality is reported in terms of gross parameters, such as BOD_5, COD, and TOC. The data in Table 15 indicate that carbon adsorption achieved BOD removal efficiencies ranging from 25-95%, COD removal efficiencies ranging from 40 to 99% and TOC removal efficiencies ranging from 42-99%.

The single largest data gap discovered during the course of this study is the inadequacy of the data available for defining the effectiveness of full-scale granular-activated-carbon systems for removing specific compounds from industrial wastewater streams. Although a wide variety of compounds are reported in streams being treated by granular-activated-carbon adsorption, data concerning the removal efficiency for these compounds, with the exception of phenol, are limited. Table 16 contains a list of compounds reported in wastewater streams being treated by carbon adsorption units. Removal efficiencies for specific

TABLE 13. DESIGN CHARACTERISTICS AND OPERATIONAL PARAMETERS FOR FULL-SCALE GRANULAR-ACTIVATED-CARBON ADSORPTION SYSTEMS

Company	Location	Flow (m^3/day)	Flow (gal/day)	Pretreatment: Equalization	pH Adjustment	Filtration	API Seperation	Dissolved-Air Flotation	Biological	Clarification	Resin Adsorbers	Chemical Coagulation	Configuration: Upflow	Downflow	Series	Parallel	Expanded Bed	Pulsed Bed	Fixed Bed	Number of Adsorbers	Height (m)	Height (ft)	Diameter (m)	Diameter (ft)	Hydraulic Loading (m^3/(min)/m^2)	Hydraulic Loading (gpm/ft^2)	Rate Contact time (min)
Allied	Fairfield, AL																										
	Moundsville, WV	5,184	1,370,000																								105
American Cyanamid	Bound Brook, NJ	75,686	20,000,000	●	●	●			●	●			●			●	●	●		10	12.2	40	4.9	16	0.32	8.0	30
Atlantic Richfield	Carson, CA	15,894	4,200,000				●	●				●		●		●				12	7.0	23			0.07	1.69	50
Beckman Instrument Co.	Porterseville, CA	34.0	9,000																								
British Petroleum[a]	Marcus Hook, PA	3,983	1,052,460			●	●						●				●	●	●	3	19.8	65	3.0	10	0.13	3.10	109
Burlington AAP	Burlington, IA	27.5	7,267			●							●				●		●	4	3.0	10	0.6	2	0.33	8.1	9
C. M. Kosland	Carlisle, PA	606	160,000																	4							
Dow Chemical	Midland, MI	545	144,000											●	●				●	4	6.1	20	2.4	8	0.08	2.0	75
Fike Chemical	Nitro, WV	170	45,000										●		●			●		2	3.7	12	1.5	5	0.06	1.6	60
General Electric	Pittsfield, MA																										
Georgia Pacific	Conway, NC																				9.1	30	3.0	10			
Hardewicke Chemical	Elgin, SC	76	20,000										●					●		2							
Hercules	Hattiesburg, MS	9,809	2,592,000	●				●					●			●		●		3	21.3	70	3.7	12	0.27	6.6	50
Joliet AAP	Joliet, IL																										
Kansas AAP	Parsons, KS																										
Liquified Coal Dev. Corp.	Captina, WV	50.5	13,350				●			●									●								
Matlock	Swedesboro, NJ	57	15,000	●	●	●	●	●				●								2							
Mobay Chemical	New Martinsville, WV	18,921	5,000,000										●			●	●			2	13.7	45	5.5	18	0.28	6.8	30
Monsanto	Anniston, AL	246	65,000																								
Neville Chemical	Neville Island, PA	189	50,000	●		●	●						●		●				●	2	3.3	11	3.0	10	0.02	0.44	170
Owens Corning	Anderson, SC	1,607	424,800	●					●	●		●			●					3	6.1	20	3.0	10	0.15	3.75	40
Palisades Industries	Peace Dale, RI	284	75,000																	4							
Reichhold	Tuscaloosa, AL	1,892	500,000	●	●					●			●			●		●		2	11.0	36	3.7	12	0.06	1.5	173
Republic Steel	Cleveland, OH															●				2							
Rhodia	Freeport, TX	191	50,400	●	●									●	●				●	2							130
	Portland, OR	378	100,000										●		●				●	2	10.7	35	2.4	8	0.06	1.4	260
Schenectady Chemical	Rotterdam Junction, NY	83	22,000																								
Sherwin Williams	Chicago, IL	219	42,000											●	●				●	2	9.1	30	1.2	4	0.13	3.2	140
Stauffer Chemical	Gallipolis, WV	1,907	500,000		●				●											4							
	Skaneateles Falls, NY	30	8,000																								
Stepan Chemical	Fieldsboro, NJ	47	15,000											●	●				●								540
Stephen Leedum Carpet	Southhampton, PA	1,892	500,000										●					●		1					0.19	4.7	
Tooele AAP	Tooele, UT																										
Velvet Textile	Blackstone, VA	227	60,000	●	●	●							●					●		1	6.7	22	2.9	9.5			
Vicksburg Chemical	Vicksburg, MS	38	10,000														●										
Unidentified (2)		5,449	1,440,000																	2					0.18	4.4	60
Unidentified (3)		436	115,200	●		●					●		●							2							
Unidentified (4)		1,090	288,000		●	●				●										1	2.4	8.0	2.4	8.0			
Unidentified (7)													●							2					0.02	.60	760
Unidentified (8)																									0.01	.32	479
Unidentified (9)																●					3.0	10	.61	2	0.09	2.1	35
Unidentified (10)																●	●			2					0.03	.66	230
Unidentified (11)				●	●	●										●	●								0.02	.30	450
Unidentified (12)																●	●			2						.51	292

[a]Data reported are for period January 1, 1975, to December 31, 1975.

TABLE 14. CARBON USAGE DATA AND COST DATA FOR FULL-SCALE GRANULAR-ACTIVATED-CARBON SYSTEMS

Company	Carbon: Calgon F-300	Calgon F-400	Westvaco WV-G	Westvaco WV-L	ICI Darco 4x8	Nitco	Carbon Inventory (kg)	Carbon Inventory (lb)	Carbon Exhaustion Rate (kg/m^3)	Carbon Exhaustion Rate (lb/1000 gal)	Regeneration Technique: Multiple Hearth	Rotary Kiln	Fluidized Bed	Off-site Thermal	Solvent	Caustic	None	Carbon Loss Per Regeneration Cycle %	Costs: Utilities	Capital	Operating	Year
Allied						•																
American Cyanamid							770,975	1,700,000	2.47	4.25	•											
Atlantic Richfield	•						272,108	600,000	5.52	9.5	•									$23,000,000	$9,000,000	1977
Bechman Instrument Co.																				1,160,000	41,894	1971-1973
British Petroleum[a]	•						136,054	300,000					•									
Burlington AAP							1,360	3,000	3.2	5.6									223,980	1,812,000	223,890	1973-1974
C.H. Masland		•					1,814	4,000														
Dow Chemical		•			•		24,489	54,000	9.6	16.4				•								
Fike Chemical							5,442	12,000	7.75	13.3		•								592,000	240,780[b]	1971
General Electric	•												•									
Georgia Pacific																						
Hardewicke Chemical		•					18,140	40,000						•								
Hercules		•					190,476	420,000	4.71	8.1		•	•					3-5	857,936	1,422,000	362,232	1973-1975
Joliet AAP																						
Kansas AAP																						
Liquified Coal Dev. Corp.																						
Matlock	•	•																				
Mobay Chemical							272,108	600,000	2.6	5.2			•									
Monsanto	•																				66,302[c]	
Neville Chemical	•						18,140	40,000	7.75	13.33				•								
Owens Corning							27,210	60,000					•									
Palisades Industries		•																				
Reichhold	•						112,471	248,000	40.7	70		•										
Republic Steel									3.1	5.3								5.0	72,000	900,000	542,000	1971-1974
Rohm	•						18,140	40,000														
		•					16,326	36,000	9.1	15.7		•	•									
Schenectady Chemical	•																					
Sherwin Williams			•				5,442	12,000	34	59			•					5.5	$9,000[d]	300,000		1971
Stauffer Chemical							36,281	80,000						•								
	•																			144,000	29,300	1973
Stepan Chemical	•												•									
Stephen London Carpet		•					22,675	50,000	252	433	•											
Tooele AAP									0.20	0.55	•											
Velvet Textile	•						18,140	40,000										5				
Vicksburg Chemical			•											•								
Unidentified (2)	•							250,000	0.81	1.39	•								15,330	100,000		1970
Unidentified (3)	•											•										
Unidentified (6)													•									
Unidentified (7)							13,605	30,000	63.9	110												
Unidentified (8)							113,378		73.8	127												
Unidentified (9)																						
Unidentified (10)							18,140	40,000						•								
Unidentified (11)							18,140	40,000	12.3	21												
Unidentified (12)							18,140	40,000	120.3	207												

[a] Data reported are for period January 1, 1975 to December 31, 1975.

[b] Net operating cost of $62,890 per year.

[c] Based on capacity operation at cost of $3.20/$m^3$ ($12.11/1000 gal).

[d] 1978 operating costs.

TABLE 15. CONTAMINANT REMOVAL PERFORMANCE DATA FOR FULL-SCALE GRANULAR-ACTIVATED-CARBON SYSTEMS

Company	BOD_5				COD				TOC				TSS				Oil and Grease				Phenol			
	Influent (mg/liter)	Effluent (mg/liter)	Removal (%)	Loading (g/g of carbon)	Influent (mg/liter)	Effluent (mg/liter)	Removal (%)	Loading (g/g of carbon)	Influent (mg/liter)	Effluent (mg/liter)	Removal (%)	Loading (g/g of carbon)	Influent (mg/liter)	Effluent (mg/liter)	Removal (%)	Loading (g/g of carbon)	Influent (mg/liter)	Effluent (mg/liter)	Removal (%)	Loading (g/g of carbon)	Influent (mg/liter)	Effluent (mg/liter)	Removal (%)	Loading g/g of carbon
Allied																								
American Cyanamid	33																							
Atlantic Richfield					250	50	80	0.26																
Beckman Instrument Co.																								
British Petroleum[a]					331	195	40		122	71	42		48	45	6		30	14	53					
Burlington AAP					198	9.8	95	0.28	62.6	5.5	91	0.08	13.1	5.9	55									
C. H. Masland					550	280	49	1.6																
Dow Chemical																					300	4.0	98	0.167
Fike Chemical																								
General Electric																								
Georgia Pacific																						0.11		
Hardewicke Chemical	3000	371	88		7500				2500				100											
Hercules	300	82	73		752	160	79	0.90	203	42	79	0.25					28.1	2.2	92		4.7	0.58	88.0	0.004
Joliet AAP																								
Kansas AAP																								
Liquified Coal Dev. Corp.																					290	0.10	99.9	
Matluck		925			2300	1225	63																0.10	
Mobay Chemical																								
Monsento																								
Neville Chemical	600	250	58	0.22													10	5	50			0.10	99	0.009
Owens Corning			25												15				10			0.02		
Palisades Industries							42																	
Reichhold	1643	411	75	0.16	3773	377	90	0.43													420	4.2	99	0.05
Republic Steel																								
Rhodia	550	24.9	95		1550	70	95		600	48	92			69			5	2.9	42					
	2000				3600																52.9	4.0	92	0.026
Schmectady Chemical																								
Sherwin Williams																								
Stauffer Chemical																								
Stepan Chemical																								
Stephen Leedom Carpet									250	5	98													
Tooele AAP																								
Velvet Textile									175				90											
Vicksburg Chemical																								
Unidentified (2)																								
Unidentified (3)																								
Unidentified (4)																					77.9	2.3	97	0.006
Unidentified (7)	1630	780	52	0.06	5780	2120	63	0.28	2220	524	76	0.13												
Unidentified (8)					5770	320	94	0.37	698	86	88	0.04												
Unidentified (9)																								
Unidentified (10)	301	109	64		8250	1394	83		1665	291	83		318	3	99									
Unidentified (11)		889			4750	808	83		1650	153	91		69	47	32						129	4.3	97	
Unidentified (12)	193	9.2	95		4880	31	99	0.20	2170	15	99	0.09	674	6.6	99									

[a]Data reported are for period January 1, 1975, to December 31, 1975.

TABLE 16. COMPOUNDS REPORTED IN WASTESTREAMS BEING TREATED BY FULL-SCALE GRANULAR-ACTIVATED-CARBON UNITS[a]

Pollutant	Concentration (mg/l) Influent	Effluent	Removal (%)	Company	City	State
Acetic acid				Dow Chemical	Midland	MI
Acetic acid				Fike Chemical	Nitro	WV
Acetone	10			Dow Chemical	Midland	MI
Aldrin	0.0085	0.00019	97.8	EPA Emer. Resp. Unit		
Aniline		1		Allied Chemical	Moundsville	WV
Aniline				Fike Chemical	Nitro	WV
Atrazine	29.5	8.78	70.2	Unidentified (13)		
Benzene	10	1		Dow Chemical	Midland	MI
Benzene	0.001	0.0001	90	EPA Emer. Resp. Unit		
Benzene	590	210	64	Hercules	Hattiesburg	MS
Benzene	0.010	0.100		Unidentified (1)		
Butanol				Fike Chemical	Nitro	WV
Butyl acetate				Fike Chemical	Nitro	WV
Para-Butylaniline				Hardewicke Chemical	Elgin	SC
N-Butylaniline				Hardewicke Chemical	Elgin	SC
Butylphenol	0.300	0.015	95	EPA Emer. Resp. Unit		
Carbofuran	2,250	0.46	99.9	Unidentified (12)		

[a]See Appendix B for operating data and other performance data.

(Continued)

Table 16. (Continued)

Pollutant	Concentration (mg/l) Influent	Effluent	Removal (%)	Company	City	State
Carbon tetrachloride		0.6		Allied Chemical	Moundsville	WV
Carbon tetrachloride	0.0011	0.0001	90.9	EPA Emer. Resp. Unit		
Carbon tetrachloride	4.34	1.81	58	Unidentified (1)		
Chloramines				Velvet Textile	Blackstone	VA
Chlordane	0.013	0.00035	97.3	EPA Emer. Resp. Unit		
Chlorocresol				Rhodia	Portland	OR
Chloroform		0.9		Allied Chemical	Moundsville	WV
Chloroform	190.32	136.07	29	Unidentified		
para-Chloronitrobenzene	11.6	0.0093	99.9	Unidentified (8)		
Chlorophenol				Rhodia	Portland	OR
2-Chlorophenol	8.67	0.62	92.8	Unidentified (1)		
4-Chlorophenol	5.64	0.010	99.8	Unidentified (1)		
Chlorophenol				Neville Chemical	Neville Island	PA
Cresol	0.23	0.0081	96.5	EPA Emer. Resp. Unit		
Cresol				Neville Chemical	Neville Island	PA
Cresol	16.5	0.62	96.2	Rhodia	Portland	OR
para-Cresol	5,000	350	93	Sherwin Williams	Chicago	IL

(Continued)

Table 16. (Continued)

Pollutant	Concentration (mg/l) Influent	Effluent	Removal (%)	Company	City	State
Cyclohexylamine				Fike Chemical	Nitro	WV
Cyclotetramethylene tetranitroamine (HMX)				Iowa AAP	Burlington	IA
Cyclotrimethylene trinitroamine (RDX)	89.5	32.7	64	Iowa AAP	Burlington	IA
2,4-D	3,600	0.010	>99.99	Unidentified (1)		
2,4-D	58.4	0.037	99.9	Unidentified (7)		
2,4-D, 2,6-D-Acids (mixed)	460			Rhodia	Portland	OR
2,4-D-Butyl ester	0.01	0.010		Unidentified (1)		
2,4-D-Isooctyl ester	1.86	0.586	69	Unidentified (1)		
2,4-DB	474	0.034	99.99	Unidentified (1)		
2,4-DB-Isooctyl ester	0.01	0.01		Unidentified (1)		
DEET	218	1.26	99.4	Unidentified (11)		
Diallyl phthalate				Hardewicke Chemical	Elgin	SC
Dichlorobenzene		6		Allied Chemical	Moundsville	WV
Dichlorobenzene				Monsanto	Anniston	AL
ortho-Dichlorobenzene				Unidentified (4)		
para-Dichlorobenzene				Unidentified (4)		

(Continued)

Table 16. (Continued)

Pollutant	Concentration (mg/l) Influent	Effluent	Removal (%)	Company	City	State
2,6-Dichlorophenol	3.47	0.26	92.5	Unidentified (1)		
2,4-Dichlorophenol	42.6	0.64	98.5	Unidentified (1)		
Dicofol	17.2	10.5	39	Unidentified (9)		
Dieldrin	0.011	0.00001	99.99	EPA Emer. Resp. Unit		
Diethyl formamide				Fike Chemical	Nitro	WV
Diethyl toluamide				Hardewicke Chemical	Elgin	SC
Diethylamine				Fike Chemical	Nitro	WV
Dimethylamine				Fike Chemical	Nitro	WV
Dimethylaniline	0.38	0.023	93.9	EPA Emer. Resp. Unit		
Dimethylphenol	1.22	0.0054	99.6	EPA Emer. Resp. Unit		
Dinitrobutylphenol	0.008	0.000002	99.98	EPA Emer. Resp. Unit		
Dinitrocresol		0.4		Allied Chemical	Moundsville	WV
Dinitrotoluene		14.5		Allied Chemical	Moundsville	WV
Dinitrotoluene (DNT)				Iowa AAP	Burlington	IA
1,3-Dioxane				Owens-Corning	Anderson	SC
Dioctyladipate	0.36	0.32	11	EPA Emer. Resp. Unit		
Diphenylamine				Fike Chemical	Nitro	WV

(Continued)

Table 16. (Continued)

Pollutant	Concentration (mg/l) Influent	Effluent	Removal (%)	Company	City	State
Ethanol				Fike Chemical	Nitro	WV
Ethyl acetate				Fike Chemical	Nitro	WV
Ethyl acrylate				Fike Chemical	Nitro	WV
Ethyl chloroacetate				Fike Chemical	Nitro	WV
Ethylamine				Fike Chemical	Nitro	WV
Ethylenediamine				Fike Chemical	Nitro	WV
Formaldehyde				Fike Chemical	Nitro	WV
Fumaric acid		1		Allied Chemical	Moundsville	WV
Heptachlor	0.0061	0.00006	99	EPA Emer. Resp. Unit		
Isopropanol				Fike Chemical	Nitro	WV
Kepone	4	0.0001	99.98	EPA Emer. Resp. Unit		
Maleic acid		1		Allied Chemical	Moundsville	WV
Malic acid		45		Allied Chemical	Moundsville	WV
Methanol				Fike Chemical	Nitro	WV
Methyl cyclohexanone		1		Allied Chemical	Moundsville	WV
Methylene chloride		0.9		Allied Chemical	Moundsville	WV
Methylene chloride	0.19	0.051	73	EPA Emer. Resp. Unit		

(Continued)

Table 16. (Continued)

Pollutant	Concentration (mg/l) Influent	Effluent	Removal (%)	Company	City	State
Methylene chloride	108	29	73	Unidentified (1)		
Methylene dianiline		2		Allied Chemical	Moundsville	WV
Monochlorobenzene		1		Allied Chemical	Moundsville	WV
Monochlorobenzene				Unidentified (4)		
Monomethylamine				Fike Chemical	Nitro	WV
Mononitrotoluene		4		Allied Chemical	Moundsville	WV
Nitrobenzene		3		Allied Chemical	Moundsville	WV
para-Nitrophenol				Monsanto	Anniston	AL
Octyl alcohols	440			Rhodia	Portland	OR
Octyl chloride				Hardewicke Chemical	Elgin	SC
PCB	0.4	0.000075	99.98	EPA Emer. Resp. Unit		
PCB	0.019	0.0001	99.5	EPA Emer. Resp. Unit		
Pentachlorophenol	10	0.0001	99.98	EPA Emer. Resp. Unit		
Pentachlorophenol	120	49	59	Hercules	Hattiesburg	MS
Phenamines				Velvet Textile	Blackstone	VA
Phenol	26.6	1.3	95	Fike Chemical	Nitro	WV
Phenol	2500			Georgia Pacific	Conway	NC

(Continued)

Table 16. (Continued)

Pollutant	Concentration (mg/l) Influent	Effluent	Removal (%)	Company	City	State
Phenol		0.11		Hardewicke Chemical	Elgin	SC
Phenol	4.7	0.58	88	Hercules	Hattiesburg	MS
Phenol	290	0.1	99.9	Liquified Coal Dev. Corp.	Captina	WV
Phenol		0.1		Matlock	Swedesboro	NJ
Phenol	15	0.1	99	Neville Chemical	Neville Island	PA
Phenol		0.02		Owens-Corning	Anderson	SC
Phenol				Allied Chemical	Fairfield	AL
Phenol		2.7		Allied Chemical	Moundsville	WV
Phenol	1.9	0.7	63	British Petroleum	Marcus Hook	PA
Phenol	32	12.9	60	British Petroleum	Marcus Hook	PA
Phenol	20	0.023	99.9	British Petroleum	Marcus Hook	PA
Phenol	12	4.5	63	British Petroleum	Marcus Hook	PA
Phenol	14	15		British Petroleum	Marcus Hook	PA
Phenol	300	4	98.6	Dow Chemical	Midland	MI
Phenol	420	4.2	99	Reichhold	Tuscaloosa	AL
Phenol	53	4	92	Rhodia	Portland	OR
Phenol	78	2.3	97	Unidentified (7)		

Data taken at different time periods; see Appendix A.

(Continued)

Table 16. (Continued)

Pollutant	Concentration (mg/l) Influent	Effluent	Removal (%)	Company	City	State
Phenol	129	4.3	97	Unidentified (11)		
Phenol	0.14	0.0001	99.92	EPA Emer. Resp. Unit		
Phenol	52.9	0.69	98.7	Rhodia	Portland	OR
Phenol	2.7	0.11	95.9	Unidentified (1)		
Bis(2-ethylhexyl)phthalate		330		Hercules	Hattiesburg	MS
Piperonyl butoxide				Hardewicke Chemical	Elgin	SC
Piperonyl butoxide	7.6	0.01	99.9	Unidentified (11)		
Propylenediamine				Fike Chemical	Nitro	WV
Resorcinol				Neville Chemical	Neville Island	PA
Tetrachlorobenzene				Unidentified (4)		
Tetryl				Iowa AAP	Burlington	IA
Toluene		1		Allied Chemical	Moundsville	WV
Toluene	0.12	0.0003	99.8	EPA Emer. Resp. Unit		
Toluene	2,500	630	75	Hercules	Hattiesburg	MS
Toluene	0.016	0.019		Unidentified (1)		
Toluene diamine		1		Allied Chemical	Moundsville	WV
Toluidine		1		Allied Chemical	Moundsville	WV

(Continued)

Table 16. (Continued)

Pollutant	Concentration (mg/l) Influent	Effluent	Removal (%)	Company	City	State
Toxaphene	0.036	0.001	97.2	EPA Emer. Res. Unit		
Trichlorobenzene		1		Allied Chemical	Moundsville	WV
Trichloroethane	0.012	0.0001	99.2	EPA Emer. Resp. Unit		
Trichloroethylene		1		Allied Chemical	Moundsville	WV
Trichloroethylene		1		Allied Chemical	Moundsville	WV
Trichloroethylene	0.021	0.0003	98.6	EPA Emer. Resp. Unit		
Trichloroethylene	0.01	0.01	-	Unidentified (1)		
2,4,6-Trichlorophenol	35	0.01	99.97	Unidentified (1)		
Trifluralin	3.4	0.004	99.9	Unidentified (10)		
Trimethylamine				Fike Chemical	Nitro	WV
Trimethylol-propane trimethylacrylate				Hardewicke Chemical	Elgin	SC
Trimethylphenol	0.13	0.01	92.3	EPA Emer. Resp. Unit		
Trinitrotoluene (TNT)	118.	2.6	98	Iowa AAP	Burlington	IA
Xylene	0.14	0.0001	99.92	EPA Emer. Resp. Unit		
Xylene				Neville Chemical	Neville Island	PA

compounds were greater than 90% for three-fourths of the entries in Table 16 for which both inlet and outlet concentrations were reported. The large variability in removal efficiencies shown on Table 16 highlights the need to develop data on actual plant effluents.

Wastewater streams containing from less than 5 mg/liter to greater than 400 mg/liter of phenol were found to have been very efficiently treated by carbon adsorption. Organic chemical manufacturing facilities report phenol removal efficiencies ranging from 88% to greater than 99%, with the average value being 96%. Effluent phenol concentration values were consistently reduced to less than 5 mg/liter, with several installations reporting effluent phenol concentrations as low as 0.10 mg/liter. The effluent concentrations which were attained were generally dictated by one of two reasons. In some cases, the effluent phenol concentration attained was set as an effluent concentration standard which was not to be exceeded. In other cases, multicomponent streams were being treated and the effluent phenol concentration was still relatively low when the column was exhausted in terms of removal of other components.

C. PLACEMENT OF ACTIVATED-CARBON COLUMNS IN WASTEWATER TREATMENT SEQUENCE

Granular-activated-carbon adsorbers are generally used in one of three modes in a wastewater treatment system:

1. pretreatment of a specific process wastewater stream before it is discharged to conventional biological treatment,
2. in conjunction with other physical-chemical process as a total physical-chemical system,
3. polishing of the effluent from a biological treatment system for the removal of refractory substances.

When activated-carbon treatment is applied to a specific process wastewater stream, several important advantages are realized. The wastewater components will be present at higher concentrations than would typically be found in end-of-pipe treatment schemes. This higher influent concentration may lead to significantly higher loadings on the carbon. Treatment at the source results in a minimum number of solutes in the feed to the adsorber, facilitating solute recovery in some cases (3, 4, 21, 27, 37, 46, 62, 63). Chemicals reported to

have been recovered by such pretreatment applications include phenol, para-cresol, paranitrophenol, paradichlorobenzene, and acetic acid.

Available data indicate that independent physical-chemical treatment systems are the most common application of granular-activated-carbon adsorption. Physical-chemical treatment is generally required when significant concentrations of toxic substances are present in the wastewater. Besides being insensitive to toxic substances, other advantages claimed for complete physical-chemical treatment systems include low sensitivity to flow and concentration variations, small space requirements, destruction of organics during thermal regeneration, and modular design for plant expansion.

The use of activated-carbon processes on wastewater previously treated by conventional secondary biological treatment is practiced for the removal of compounds that are nontoxic but are resistant to biodegradation. Carbon units in this mode are generally used for high-volume, relatively low organic concentration wastewater streams. The largest installation of this type is the system operated by American Cyanamid at their Bound Brook, NJ, facility. Although conventional secondary treatment provided a 90% reduction of BOD, carbon adsorption units were required to remove refractory organics from the 75,000-m^3/day (20 MGD) wastewater stream.

D. PRETREATMENT REQUIREMENTS

Pretreatment of wastewater streams fed to activated-carbon adsorbers is typically practiced for the removal of suspended solids, oil, and grease. It is generally recommended that suspended-solids concentrations applied to carbon columns be limited to a maximum of 50 mg/liter and that oil and grease concentrations not exceed 10 mg/liter. Both suspended solids and oil and grease may filter out on the carbon beds and create excessive pressure drop problems.

Severe reductions in adsorptive capacity have been noted in those cases where high concentrations of oil and grease have caused an apparent coating of carbon particles. In the activated-cabon adsorption system at the British Petroleum Refinery in Marcus Hook, PA, a 40% decrease in adsorption capacity was observed over an 18-month period (36). This was attributed partly to inadequate pretreatment in terms of oil and grease removal.

The data in Table 13 indicate that equalization, pH adjustment, filtration, oil flotation, chemical coagulation, and clarification are common pretreatment unit operations. Although carbon-adsorption units can be designed to meet widely fluctuating flow and organic concentration conditions, capital costs for the carbon adsorption unit are reduced when these variations are minimized by the installation of adequate equalization facilities. The adjustment of pH may be practiced to enhance adsorption of specific compounds but is more commonly used to reduce corrosion problems in adsorption equipment.

E. CARBON-COLUMN CONFIGURATION

Activated-carbon treatment systems may employ columns arranged in a variety of configurations. Beds may be arranged in either a series or parallel mode, and the flow may be either up or down. Fixed beds and pulsed (moving) beds have been used extensively, with expanded beds used to a lesser degree. As is indicated in Table 13, there is no "typical" configuration; rather, each system is designed to meet a specific treatment objective.

Fixed beds in parallel are routinely used when the effluent breakthrough curve exhibits a sharp profile. When the lead adsorber is exhausted, it is taken off-line for regeneration, and the flow is switched to the second column in series. Following regeneration the fresh column is placed on-stream at the end of the treatment sequence. The carbon therefore moves countercurrent to the flow of the wastewater.

Large-volume plants typically employ columns connected in parallel. Each column receives the same feed stock and discharges into a common manifold. The number of columns in parallel range from 2 to 12 in current practice.

The pulsed-bed configuration is a modification of the countercurrent principle. The wastewater flows upward through the column, and spent carbon is periodically withdrawn from the bottom of the carbon. The volume of carbon withdrawn per pulse is typically about 5 to 10% of the total volume of carbon in the column. Every time that spent carbon is discharged, fresh carbon is added at the top. This treatment mode comes closest to completely exhausting the carbon-adsorption capacity if adsorber is properly sized.

If a wastewater stream is low in suspended solids, a downflow contactor may serve the dual purpose of adsorption and filtration, thereby reducing capital costs. However, use of a downflow system necessitates regeneration of the entire contents of a carbon column on a batch basis.

Upflow expanded beds have the advantage of being able to handle higher suspended-solids concentrations than can be tolerated in fixed-bed systems. Operating experience at American Cyanamid (Bound Brook, NJ) and Mobay (New Martinsville, WV) indicates that hydraulic loading rates of 0.28 to 0.33 $m^3/(min)(m^2)$ (6.8 to 8.0 gpm/ft) are required for adequate bed expansion.

F. CONTACT TIME

Due to high organic concentrations in typical industrial wastewaters, contact times are generally longer than those experienced in municipal practices. The contact times tabulated in Appendix B are total adsorption system contact time. Contact time is calculated on an empty-adsorber basis and the volume occupied by the carbon is ignored. Figure 12 shows a frequency distribution of contact times found for full-scale systems and indicates that 50% of the installations reporting contact time utilize values of less than 100 min. Contact times greater than 230 min may be attributed to applications where a high degree of pollutant removal is required, such as for pesticide removal. Long contact times may also be due to the use of standardized adsorbers (such as in service systems) where the contact time is not a design parameter but rather depends on the flow and number of columns.

G. HYDRAULIC LOADING RATE

The hydraulic loading rate is generally dictated by the dimensions of the adsorber, the contact time required to produce an acceptable effluent, and head-loss considerations that are influenced by the mode of operation (upflow, downflow, packed bed, expanded bed) and the carbon particle size. Figure 13 indicates that hydraulic loading rates found in practice vary from less than 0.02 $m^3/(min)(m^2)$ (0.5 gpm/ft^2) up to 0.33 $m^3/(min)(m^2)$ (8 gpm/ft^2). Fifty percent of the installations using granular-activated-carbon adsorption columns for which hydraulic loading rate was found report using hydraulic loading rates of less than 0.06 $m^3/(min)(m^2)$ (1.5 gpm/ft^2).

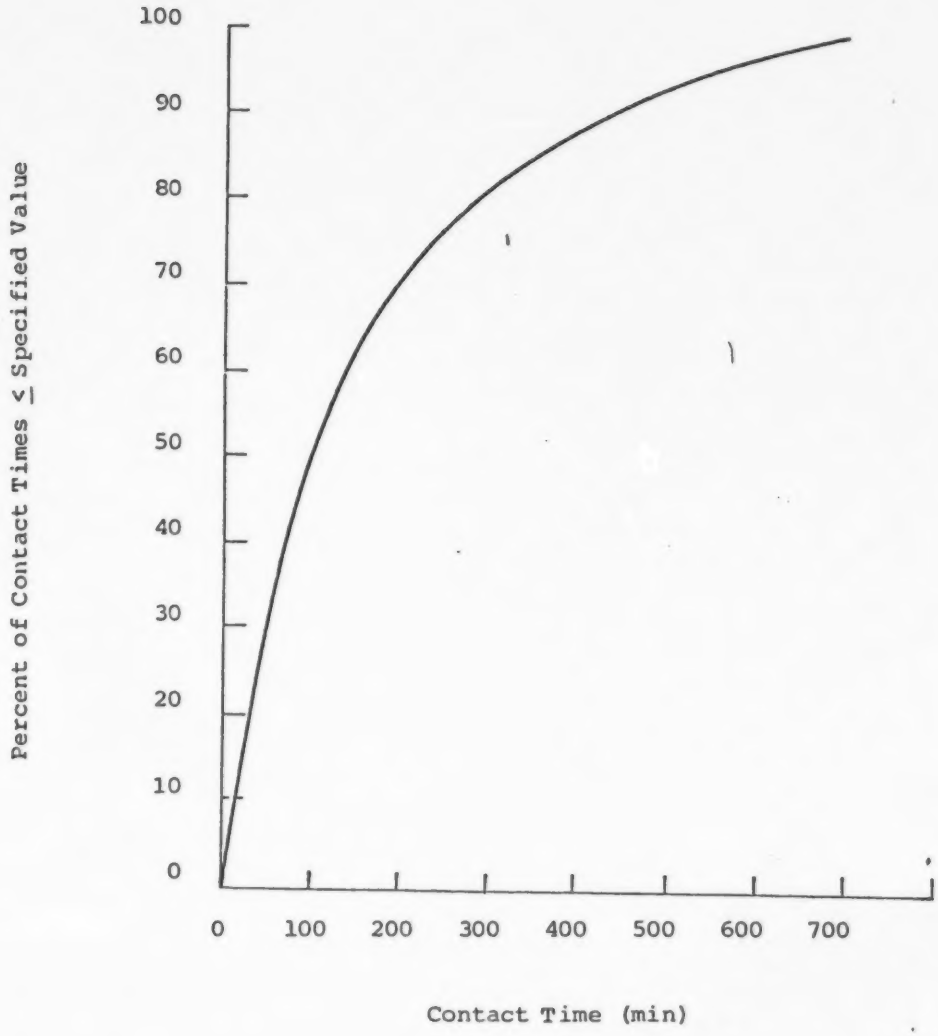


Figure 12. Frequency distribution of contact times

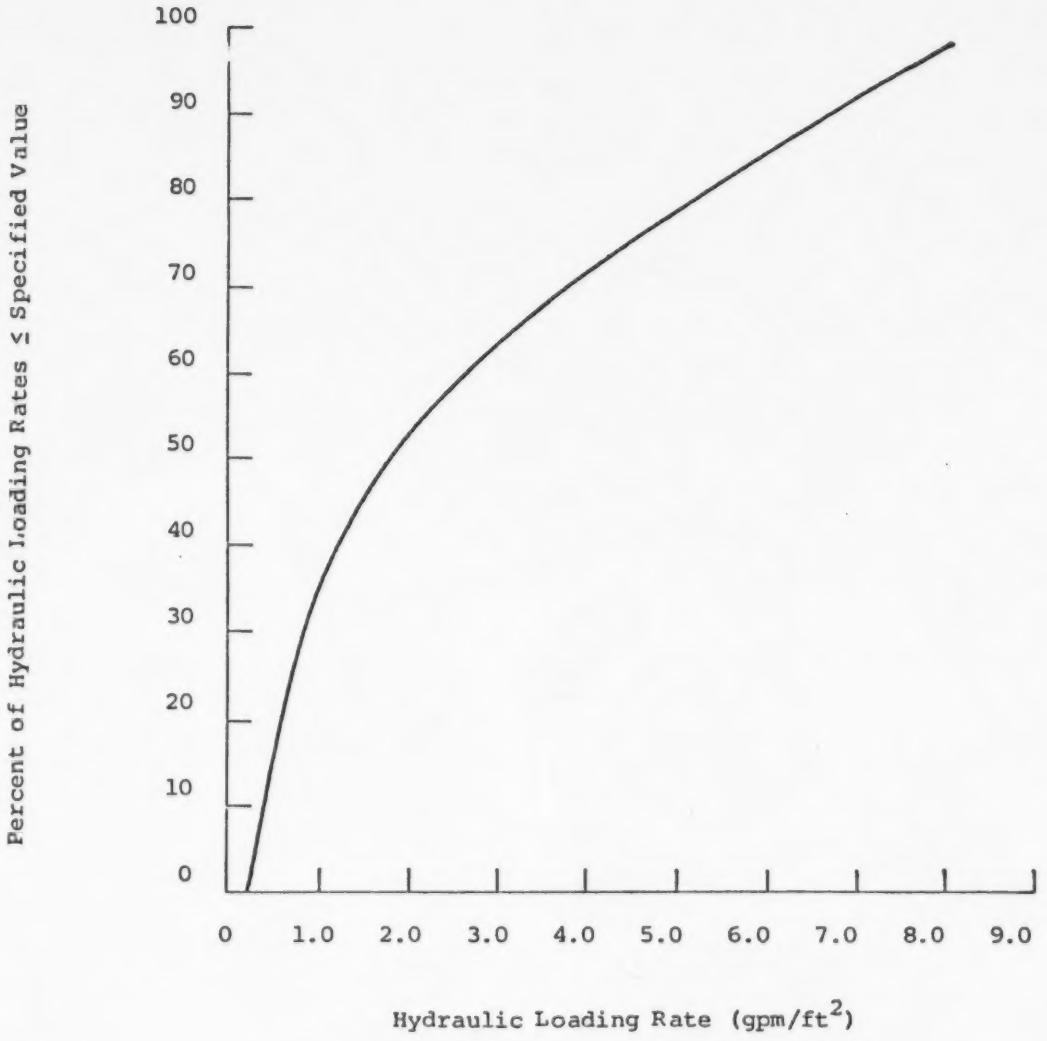


Figure 13. Frequency distribution of hydraulic loading rates

H. COLUMN DIMENSIONS

The height of activated-carbon columns was found to range from 2.4 to 21.3 m (8 to 70 ft), with typical units ranging in height from 6.1 to 12.2 m (20 to 40 ft). The diameter of industrial columns was found to range from 0.6 to 5.5 m (2 to 18 ft). Typical units are less than 3.7 m (12 ft) in diameter.

I. REGENERATION

Spent-carbon regeneration may be accomplished by either thermal or chemical means. Installations utilizing carbon adsorption for treatment of highly heterogeneous wastewater streams usually employ thermal regeneration techniques. Six installations are reported to be using chemical regeneration systems.

Thermal reactivation is the more commonly used method because it can reactivate carbon regardless of the nature of the adsorbed solute. Three different types of thermal regeneration equipment are in current use for reactivating carbon used in treating organic chemical industry wastewaters: multiple-hearth furnaces, fluidized-bed furnaces, and rotary-kiln furnaces.

In 1978 it was reported (142) that approximately 20 thermal reactivation systems were installed in the United States at industrial facilities. Two installations are reported to be using fluidized-bed systems, and one rotary-kiln furnace has been reported. No performance data were found for either the fluidized-bed installations or the rotary-kiln furnace.

The most common technique for regenerating spent activated carbon involves the use of a multiple-hearth furnace, which consists of a series of from four to eight circular hearths placed one above the other. Dewatered carbon is introduced on the top hearth and is successively moved to lower hearths by rotating rabble arms.

The thermal regeneration process involves three steps: drying, baking, and activation. During the drying step, water entrained in the pores is driven off. The baking step involves the pyrolysis of the organic adsorbate and the evolution of gases. During this step a carbon residue is formed within the carbon pores. The baking process occurs at temperatures ranging from 212 to

1500°F. The activation step seeks to oxidize the residual carbon that remains in the activated-carbon pores. Carbon dioxide, steam, and air are used as activating agents. The quantity of oxygen present in the combustion chamber is typically kept at less than 1 or 2% of the gas volume in order to prevent uncontrolled combustion of the activated carbon. Approximately 1.0 kg of steam per kg of carbon is often recommended for use (129). Activation temperatures may range from 1500 to 1800°F.

Multiple-hearth furnaces are normally equipped with afterburners and wet scrubbers. The afterburner is used to combust organic components, and the wet scrubber reduces dust, acid gases, and odorous emissions. A recent pilot study was undertaken in order to determine the conditions necessary to safely incinerate reactivation off-gases. Eight toxic compounds were individually loaded on activated carbon and the carbon was then thermally regenerated. Of the eight compounds, five were not found in orginal form in the off-gas. The other three compounds were reduced by at least 98% by the afterburner (132).

A certain quantity of carbon is lost during the thermal regeneration cycle due to attrition during handling, burning of carbon within the furnace, and thermal shock when the carbon is quenched following regeneration. For a well-operated on-site system, carbon losses per regeneration cycle can be held to approximately 5%. Carbon losses during off-site reactivation are reported to be in the range of 10 to 15% due to the additional handling that is required (127).

Carbon properties have also been shown to be altered by the regeneration process. When a carbon is thermally regenerated, small pores are lost mainly due to burning and in part to a buildup of inert solids. During reactivation, small pores are increased in size, increasing the number of the larger transitional pores and the surface area contained within these pores. Overall surface area is reduced, however, as a result. The data in Table 17 demonstrate the severe loss that can occur in adsorptive performance for an activated carbon system such as that at the British Petroleum Refinery in Marcus Hook, PA. After 18 months of operation the adsorptive performance of the regenerated carbon fell off by 37% for phenol removal and by 82% for COD removal. The isotherm test data in Table 18 confirm significant performance characteristic differences for the virgin carbon and the regenerated carbon.

TABLE 17. EFFECT OF REGENERATION ON BITUMINOUS COAL CARBON AND ITS PERFORMANCE AT BRITISH PETROLEUM CORPORATION REFINERY, MARCUS HOOK, PA[a]

	Virgin Carbon	Regenerated Carbon[b]	% Change
Iodine No.	950--1,000	560--680	-27 to -44
Molasses No..	230	280	+22
Phenol, % removal	99.9	63	-37
COD, % removal	71	13	-82

[a]Adapted from ref 16 by permission of the editor.

[b]After 18 months of repeated adsorption - regeneration cycles.

TABLE 18. ISOTHERM COMPARISON OF PERFORMANCE OF VIRGIN AND REGENERATED CARBON USED AT BRITISH PETROLEUM CORPORATION REFINERY, MARCUS HOOK, PA[a]

Loading (lb of impurity removed/ lb of carbon applied)	Virgin Carbon	Regenerated[b] Carbon	% Change
TOC	0.17	0.096	-44
COD	0.73	0.35	-52
Phenol	0.04	0.03	-25

[a]Adapted from ref 16 by permission of the editor.

[b]After 18 months of repeated adsorption - regeneration cycles.

Operating experience at Hercules indicated that regenerated carbon was found to be more active than virgin carbon for the removal of organics from the plant wastewater. This was attributed to the predominance of large molecules in the plant wastewater stream which were adsorbed in the large pores created by the thermal regeneration process.

The conflicting experiences reported by British Petroleum Corporation and Hercules regarding the performance of regenerated carbon points out the necessity of conducting pilot studies with regenerated rather than virgin carbon.

Thermal regeneration may either be conducted on-site or be performed at a central reactivation center by a carbon vendor for a monthly service fee. The daily quantity of carbon that must be regenerated will dictate the choice of on-site versus contract regeneration. For small systems a monthly service fee may be less than the cost of purchasing and operating reactivation equipment on-site.

Chemical-regeneration techniques may be feasible in those cases where a limited number of solutes are being adsorbed, thereby allowing the adsorbed solute to be recycled within the production process. Chemical-regeneration techniques offer certain advantages over traditional thermal-regeneration techniques. Activated carbon may be regenerated in-place, eliminating carbon losses due to attrition during handling. Capital costs are also reduced because of minimal carbon handling equipment requirements. It has been shown that over 100 cycles of adsorption and regeneration are possible without the initial carbon charge to the column being changed (21).

Two methods of chemical regeneration are presently being practiced: pH change and solvent. The pH regeneration technique has been applied to carbon loaded with phenol (21, 27, 46) and paracresol (3,4). In the phenol recovery process carbon is regenerated by a sodium hydroxide solution, which reacts with the phenol to form sodium phenate and water. The sodium phenate desorbs from the carbon and is removed by the regenerant stream. The other method of chemical regeneration involves the use of a solvent phase to desorb the organics from the carbon. Solvents reported in use include methanol and isopropanol (18, 63). Following solvent elution of the adsorbed material, the solvent may be

recovered by distillation. Steam elution is required to remove the solvent from the regenerated carbon.

J. ECONOMICS

Capital costs for carbon-adsorption systems are primarily influenced by the required hydraulic capacity, the characteristics of the wastewater, and the degree of pretreatment required. The capital costs reported in Appendix B include expenditures for pretreatment operations, as well as those for adsorption and reactivation equipment.

Operating costs for five different carbon adsorption systems are given in Tables 19 through 23. During the period from 1971 to 1974, operating costs for various systems were found to vary from $\$0.07/m^3$ to $\$0.62/m^3$ ($0.28/1000 gal to $2.98/1000 gal). The bases for reporting operating costs vary widely from installation to installation, making comparisons between different systems difficult. For example, depreciation has a major impact on operating costs but it is not always included.

Both capital and operating costs have been estimated for an on-site carbon reactivation facility (132). Capital cost information is presented in Table 24, and operating cost estimates are given in Table 25. Both capital and operating costs illustrate definite economies of scale.

TABLE 19. HERCULES CARBON ADSORPTION SYSTEM OPERATING COST 7/1/73--7/31/75[a,b]

Item	Average Cost		
	Per year	Per m^3	Per 1000 gal
Operation			
Labor	$ 27,648	$0.0063	$0.0240
Chemical control	6,444	0.0015	0.0056
Supervision	972	0.0002	0.0008
Overhead	22,908	0.0053	0.0199
Maintenance			
Labor	$ 51,144	$0.0117	$0.0444
Materials	40,284	0.0092	0.0350
Utilities			
Electricity	$ 49,836	$0.0114	$0.0433
Natural gas	8,100	0.0019	0.0070
Makeup carbon	$154,896	$0.0355	$0.1345
Total	$362,232	$0.0830	$0.3145

[a] From (23).

[b] Based on design flow of 3,156,000 gpd.

TABLE 20. ATLANTIC RICHFIELD CARBON ADSORPTION SYSTEM OPERATING COSTS[a]

Item	Average Cost		
	Per year	Per m^3	Per 1000 gal
Utilities	$10,533	$0.032	$0.12
Repair labor	5,125	0.016	0.06
Operating labor	11,721	0.037	0.14
Makeup carbon	10,890	0.034	0.13
Miscellaneous[b]	3,625	0.011	0.04
Total	$41,894	$0.130	$0.49

[a]From (33).

[b]Includes maintenance overhead, transportation overhead, and maintenance costs other than labor.

TABLE 21. REICHHOLD CARBON ADSORPTION SYSTEM OPERATING COSTS 1971--1974[a]

Item	Average Cost[b]		
	Per year	Per m^3	Per 1000 gal
Utilities	$ 72,000	$0.106	$0.40
Labor	54,750	0.079	0.30
Makeup carbon	204,400	0.296	1.12
Miscellaneous[c]	73,000	0.106	0.40
Fixed costs[d]	138,000	0.201	0.76
Total	$542,150	$0.788	$2.98

[a] From (51).

[b] Based on average flow of 1892 m^3/day (500,000 gpd).

[c] Includes maintenance, general services, administration, and overhead.

[d] Includes depreciation, insurance, and taxes.

TABLE 22. BRITISH PETROLEUM CORPORATION CARBON ADSORPTION SYSTEM OPERATING COSTS 10/1/73--9/30/74[a]

Item	Average Cost[b]		
	Per year	Per m^3	Per 1000 gal
Labor	$ 98,750	$0.0325	$0.1230
Utilities	55,410	0.0182	0.0690
Makeup carbon	36,130	0.0119	0.0450
Sludge disposal	10,510	0.0035	0.0131
Maintenance	21,580	0.0071	0.0269
Supplies	1,600	0.0005	0.0020
Total	$223,980	$0.0737	$0.2790

[a] From (36).

[b] Based on average flow of 8325 m^3/day (2,200,000 gpd). Includes costs for dual media filtration and solids dewatering.

TABLE 23. DOW CARBON ADSORPTION SYSTEM OPERATING COSTS[a]

Item	Average Cost		
	Per year	Per m^3	Per 1000 gal
Depreciation	$ 69,200	$0.383	$1.45
Maintenance	25,000	0.137	0.52
Utilities	8,600	0.048	0.18
Chemicals	104,327	0.573	2.17
Labor	0	0.000	0.00
Makeup carbon	33,653	0.185	0.70
Total	$240,780	$1.326	$5.02
Credits			
Recovery of phenate regenerant	$ 50,481	$0.278	$1.05
Salt recycle	48,077	0.264	1.00
Reduction in brine disposal cost	79,326	0.436	1.65
Total credits	$177,884	$0.978	$3.70
Net operating cost	$ 62,896	$0.348	$1.32

[a]From (21).

TABLE 24. INSTALLED CAPITAL COSTS OF REACTIVATION SYSTEMS AS OF 1978[a]

Reaction Rate (lb/day)	Cost (million $)		
	Purchased Equipment	Installation[b]	Total
5,000	$0.24	$0.61	$0.85
10,000	0.36	0.91	1.27
30,000	0.77	1.93	2.70
60,000	1.20	3.00	4.20

[a]Data taken from (142).

[b]Includes foundations, structural equipment setting, electrical, instrumentation, site preparation, engineering contractor, overhead and profit, and indirect costs.

TABLE 25. OPERATING COSTS OF REACTIVATION SYSTEMS AS OF 1978[a]

	Cost ($1000/yr) as a Function of Reactivation Rates			
	5000 lb/day	10,000 lb/day	30,000 lb/day	60,000 lb/day
Fuel, 8000 Btu/lb @ $3/$10^6$ Btu	$ 45	$ 90	$ 265	$ 525
Power, @ 3¢/kWh	10	20	50	80
Steam, 1.0 lb/lb of carbon @ $4/1000 lb of steam	10	15	45	90
Labor and supervision	110	110	110	110
Makeup carbon, 7% @ 57¢/lb	70	145	435	875
Maintenance @ 8% of capital	70	100	215	335
General plant overhead	30	50	110	200
Total operating cost	$345	$530	$1230	$2215
Operating cost, lb of carbon	0.188	0.145	0.122	0.110

[a]From (142).

IX. DISCUSSION OF POWDERED-ACTIVATED-CARBON FULL-SCALE SYSTEMS AND PILOT STUDIES

A. GENERAL

Powdered activated carbon in wastewater treatment systems has been used in an effort to expand the treatment capabilities of existing biological treatment facilities. The process generally involves the addition of powdered carbon to a biological treatment process, such as an activated-sludge unit or a rotating biological contactor. At least one facility, however, is reported (6) to be adding powdered carbon to a primary clarifier in an effort to pretreat feed going to a biological treatment system.

The powdered-carbon biological treatment process is often referred to as the PACT* process and has been patented by the E.I. du Pont Company. The applications of powdered carbon discussed here include pilot- and laboratory-scale experience, as well as full-scale tests and full-scale operating experience.

Powdered-carbon systems claim many of the same advantages that are attributed to adsorption systems using granular carbon, including removal of toxics, system stability, and operational flexibility. However, adding powdered carbon to a biological treatment system has been shown to yield significant improvement in several other key operating parameters for these systems. Improved hydraulic capacity, reduction in aerator foaming tendencies, improved sludge settling and dewatering, and improved nitrification are characteristics of powdered-carbon biological treatment systems that have been claimed by various authors (28).

There are several economic factors that favor the use of powdered-carbon systems rather than granular-activated-carbon systems. Powdered carbon can be fed on demand to meet varying organic concentrations in the feed, powdered-carbon systems require a smaller capital investment than do granular-carbon systems, and powdered carbons cost substantially less than granular carbons.

However, it will be difficult, if not impossible to assess the economics of continuous powdered-activated-carbon treatment until more data become available

---

*Du Pont service mark.

concerning the carbon regeneration phase of the treatment process. A variety of pilot-plant processes have been demonstrated for regeneration of spent powdered carbon. These include fluidized beds, multiple-hearth furnaces, transport reactor furnaces, and wet-oxidation units (8, 128, 131). Other than the multiple-hearth furnace at Du Pont in Deepwater, NJ, there are no reported full-scale powdered-carbon regeneration facilities at organic chemical production facilities.

B. FULL-SCALE OPERATING EXPERIENCE

Table 26 lists companies reported to have had experience with powdered-carbon wastewater treatment systems. With the exception of the Du Pont system in Deepwater, NJ, full-scale performance data for powdered-activated-carbon units are very limited. Other companies reporting data for full-scale systems, either on an operating or a test basis, include ICI Americas, Lion Oil, and Sun Oil. Data for these units, as well as pilot- and bench-scale studies, are tabulated in Appendix C. Due to the limited amount of data available, these units are discussed on a case-by-case basis.

1. Du Pont Chambers Works

The Du Pont Chambers Works in Deepwater, NJ, manufactures more than 2500 products, nearly all of which fall in the organic chemicals category. Most of the plant processes are on a batch basis, resulting in periodic discharges of organics, which may result in shock loads to the wastewater treatment system (28, 29, 48).

The raw wastewater typically has a pH of 2.0, a total suspended-solids concentration of 110 mg/liter, and a total BOD of 180 mg/liter. The raw wastewater from this facility contains over 50 compounds on the EPA's priority pollutant list. The average flow is 151,000 m^3/day (40,000,000 gpd).

The liquid-train treatment process begins with lime neutralization of the influent wastewater followed by polymer addition and primary clarification. The range of dosage of powdered activated carbon added to the wastewater after primary clarification is 70-150 ppm. A combined powdered-carbon—activated-sludge treatment process utilizes three parallel aerators. The hydraulic detention time in the aerators ranges from 7-9 hr and the sludge age ranges

TABLE 26. COMPANIES REPORTED TO HAVE EXPERIENCE WITH FULL-SCALE POWDERED-ACTIVATED-CARBON SYSTEMS[a]

Company	Location	Principal Product	Data Source
Ashland Chemical	Great Meadows, NJ	a	37
Dow Chemical	Freeport, TX	Organic chemicals	59
Du Pont	Deepwater, NJ	Organic chemicals	8,14,29,48
	Cleveland, OH	a	41
ICI Americas	Goldsboro, NC	Research facility	6
Koppers Chemical	Follansbee, WV	Cresols, phenol, naphthalene	37
Lion Oil	Martinez, CA	Refinery products	15
Olin Corp.	Joliet, IL	Detergents	41
Proctor and Gamble	Long Beach, CA	Fatty acids	41
	Ivorydale, OH	Fatty acids, alcohols	41
Stauffer	Coldcreek, AL	Organic chemicals	41
	Tacoma, WA	Superphosphate	41
Sun Oil	Corpus Christi, TX	Refinery products	47

[a]Incomplete information in data source.

from 20-60 days. Following the aeration basins, polymer is added to the wastewater stream before secondary clarification. The effluent from the secondary clarifiers is discharged to a holding basin and subsequently to a river. A portion of the sludge from the secondary clarifiers is recycled to the aerators, and the remainder is sent to the solids handling train. (143)

The initial unit operation of the solids handling train is a waste sludge thickening and storage tank. From the sludge thickener the sludge is pumped to filter presses, where a cake containing 40-45% solids is obtained. Filtered sludge is fed to a multiple-hearth furnace, where the biomass is oxidized and the powdered carbon is regenerated. The regenerated carbon is quenched, acid washed, and slurried and then sent to storage tanks.

Performance data for the Du Pont Chambers Works are given in Tables 27 and 28. The full-scale data in Table 27 were gathered from the plant under half-full flow-rate conditions. Also included is a comparison with bench-scale control units. One bench-scale unit operated with a carbon dosage of 150 mg/liter; the other unit was operated as a conventional biological system with no carbon addition. Both the bench-scale PACT unit and the full-scale PACT unit show dramatic reductions in color and moderate reductions in dissolved organic carbon (DOC) when compared to the performance data for the bench-scale conventional biological system. The differences observed in removal of soluble BOD obtained with all three units are within the variability of the BOD analysis in this concentration range.

The data in Table 28 were obtained during a period when the plant was operating under full flow-rate conditions. These data indicate a 96.8% reduction in soluble BOD, an 86.9% reduction in DOC, and a 76.4% reduction in color. However, it should be noted that these data, as well as those in Table 27, were taken from tests conducted with virgin carbon.

Data on the removal of 21 organic priority pollutants by the PACT process are presented in Appendix C. Greater than 90% removal of these organics is exhibited for 15 of the 21 compounds tested. The percentage removal figures for these pollutants are best-estimate values derived from grab samples and are not directly derived from the feed and effluent values listed.

TABLE 27. COMPARISON OF FULL-SCALE TEST DATA WITH BENCH-SCALE DATA FOR DU PONT CHAMBERS WORKS FOR PERIOD 3/12/77 THROUGH 3/26/77

	Full-Scale Pact Plant[b]	Bench-Scale Controls	
		Pact	Conventional Biological
Operating conditions			
Carbon dose (ppm)	182	150	0
Areation temperature (°C)	22	22	22
Hydraulic residence time (hr)	14.6	7.5	7.5
Sludge age (days)	c	8	8
Feed Quality			
BOD-soluble (mg/liter)	304	304	304
DOC (mg/liter)	214	214	214
Color (APHA)	1416	1416	1416
Effluent quality			
BOD-soluble (mg/liter)	15.2	19.3	13.8
DOC (mg/liter)	35.7	28.4	67.3
Color (APHA)	311	369	1900

[a] From ref 48.

[b] Run at half-full flow rate.

[c] No steady-state material balance available.

TABLE 28. DU PONT CHAMBERS WORKS FULL-SCALE TEST DATA FOR PERIOD 4/26/77 THROUGH 5/6/77[a]

Operating conditions	
Carbon dose (ppm)	189
Aeration temperature (°C)	28.5
Hydraulic residence time (hr)	7.5
Feed quality	
BOD-soluble (mg/l)	300
DOC (mg/l)	214
Color (APHA)	2080
Effluent quality	
BOD-soluble (mg/l)	9.6
DOC (mg/l)	28
Color (APHA)	490

[a]From (48).

The capital cost for the total PACT system at the Chambers Works was reported to be $21,900,000 in 1975-1976 dollars. However, only 20% of the capital expense (or $4,400,000) was directly attributable to the cost of the carbon feed, storage, and regeneration equipment.

The estimated operating costs for the Chambers Works wastewater treatment system in 1977 was $7,300,000.(28) Depreciation was the major operating expense, representing 36.9% of the annual operating costs. Carbon costs were estimated to be $1,400,000. This value was calculated on the basis of 170-ppm carbon dosage, with carbon costs of approximately $0.55 to $0.66/kg ($0.25 to $0.30/lb) and a 75% regeneration yield. More recent data, however, indicate that the Chambers Works uses 68% virgin carbon and 32% regenerated carbon (29). This indicates relatively high carbon regeneration losses and subsequently higher carbon costs.

Although the use of carbon may appear to increase the operating cost, Hutton (28, 29) points out that the PACT process may reduce other operating expenses commensurately. Savings may be realized on defoamers, coagulants, and sludge handling chemicals. PACT may also reduce capital costs associated with conventional activated-sludge processes. Less process equipment may be required to provide protection from hydraulic or toxic overloads. If carbon is thermally regenerated, sludge disposal will be an additional benefit of the thermal oxidation process (28).

2. Lion Oil Company, Martinez, CA

The Lion Oil Company has reported (15) the startup of a wastewater treatment unit using powdered activated carbon, which is added to a rotating biological contactor. Studies indicated that the rotating biological contactor effluent would meet both COD and fish toxicity limits except during the winter months. From capital cost considerations, possible ease of handling, and an indication that relatively small quantities would be required, the decision was made to use powdered carbon on a periodic and throwaway basis.

3. Sun Oil Company, Corpus Christi, TX

Full-scale tests were conducted (47) with powdered activated carbon added to an activated-sludge system at Sun Oil Company's Corpus Christi, TX, refinery. The

tests were conducted in order to find a method of complying with 1977 NPDES permit limitations for effluent suspended solids.

Three separate trials were conducted with various powdered-carbon dosages. Since it was not possible to operate a parallel control unit with no carbon added to it, the data from the activated sludge unit for the 30 days preceding each trial are taken as a base case. Test conditions for these trials are listed in Table 29. The performance data for the three trials are compared in Tables 30, 31, and 32. The powdered-carbon system consistently had better effluent quality in terms of suspended solids, COD, and BOD than did the control unit. The consistency of the powdered-activated-carbon unit during the third trial is illustrated by the frequency distribution in Fig. 14. The effluent suspended-solids concentration in the test unit varied from approximately 20 mg/liter to approximately 65 mg/liter, whereas the effluent suspended-solids concentration in the control unit varied from 30 mg/liter to 220 mg/liter.

4. ICI Americas, Inc., Goldsboro, NC

ICI Americas operates a pesticide research facility that generates wastewater contaminated with a variety of pesticides and organic solvents. Biological treatability studies indicated that the wastewater was toxic and that biological treatment alone was not feasible. Activated-carbon studies indicated that nearly 100% reduction in pesticide contamination could be obtained with carbon dosages of 1000 ppm.

The wastewater treatment process that was subsequently developed uses both activated-carbon adsorption and biological treatment. The wastewater is equalized and then fed to a carbon-contact clarifier, where 1.0 to 1.5 mg/liter of anionic polyelectrolyte and 1000 mg/liter of powdered activated carbon are added to the stream. The carbon-contact clarifier provides 2 hr of detention in the carbon- contact zone and 4 hr of detention in the clarification zone. Settled carbon is sent to sand drying beds, and the effluent is fed to a second flow equalization basin. An activated-sludge unit, secondary clarifier, mixed-media filter, granular-activated-carbon column, and storage pond are subsequent unit operations in the treatment system. The effluent is disposed of by spray irrigation.

TABLE 29. SUMMARY OF POWDERED-ACTIVATED-CARBON (PAC) ADDITION TRIALS AT SUN OIL COMPANY REFINERY, CORPUS CHRISTI, TX[a]

AERATION SYSTEM, 450 PPM OF PAC
RECYCLE SYSTEM, 1000 PPM OF PAC

	Period	Duration (days)	Average Carbon Dosage (ppm)	Treatment Cost (¢/1000 gal)[b]
Trial 1	Sept.—Nov. 1974	82	24	4.3
Base case 1	August 1974	30		
Trial 2	May 1975	28	19	3.5
Base case 2	April 1975	30		
Trial 3	August 1975	26	9	1.7
Base case 3	July 1975	31		

[a]From ref 47.

[b]At 22¢/lb. (Carbon cost only)

TABLE 30. EFFECT OF POWDERED CARBON ON DAILY AVERAGE EFFLUENT SUSPENDED SOLIDS AT SUN OIL COMPANY REFINERY, CORPUS CHRISTI, TX[a]

	Flow (gpm)	Effluent (ppm)	Effluent (lb/day)	Reduction (%)
Base case 1	626	115	861	
Trial 1	629	50	381	55.7
Base case 2	645	163	1262	
Trial 2	657	72	565	55.2
Base case 3	839	79	799	
Trial 3	799	42	405	49.3

[a]From ref 47.

TABLE 31. EFFECT OF POWDERED CARBON ON DAILY AVERAGE EFFLUENT COD AT SUN OIL COMPANY REFINERY, CORPUS CHRISTI, TX[a]

	Flow	Influent		Effluent		Removal	Reduction
	(gpm)	(ppm)	(lb/day)	(ppm)	(lb/day)	(%)	(%)
Base case 1	626	459	3445	170	1277	62.9	
Trial 1	629	457	3446	135	1020	70.4	20.1
Base case 2	645	343	2658	266	2059	22.5	
Trial 2	657	444	3500	183	1445	58.7	29.8
Base case 3	839	367	3698	166	1670	58.8	
Trial 3	799	379	3632	112	1073	70.5	35.7

[a]From ref 47.

TABLE 32. EFFECT OF POWDERED ACTIVATED CARBON ON DAILY AVERAGE EFFLUENT BOD_5 AT SUN OIL COMPANY REFINERY, CORPUS CHRISTI, TX[a]

	Flow	Influent		Effluent		Removal	Reduction
	(gpm)	(ppm)	(lb/day)	(ppm)	(lb/day)	(%)	(%)
Base case 1	626	152	1144	15	116	89.9	
Trial 1	629	213	1607	15	114	92.9	1.7
Base case 2	645	152	1173	30	232	80.2	
Trial 2	657	227	1898	13.5	113	94.0	51.3
Base case 3	839	188	1895	12	124	93.5	
Trial 3	799	207	1981	3	30	98.5	75.8

[a]From ref 47.

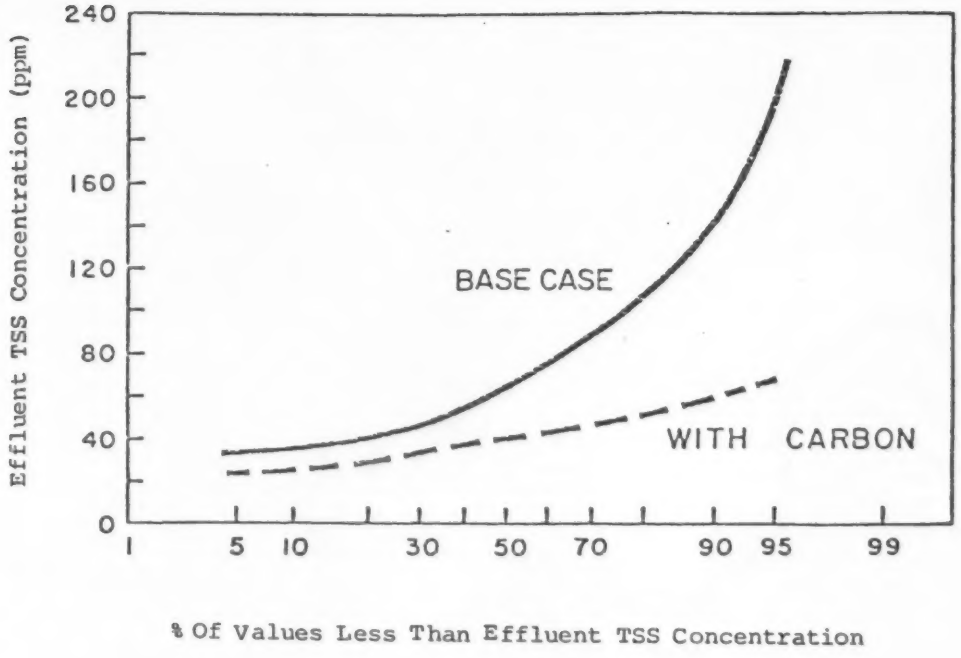


Figure 14. Effect of powdered carbon on effluent TSS (from ref 47)

Performance was monitored over a 2½-month period at several different points in the treatment process. Performance measured across the carbon-contact clarifier indicated an 85.5% reduction in BOD and a 72% reduction in COD.

C. PILOT-SCALE AND BENCH-SCALE EXPERIENCE

1. Amoco, Texas City, TX

A pilot-plant program was conducted at Amoco's Texas City, TX, refinery utilizing powdered-carbon activated-sludge units. In the first phase of the study five aerators were operated in parallel, with four of them receiving a 100-mg/liter dose of different types of powdered carbon and the fifth unit serving as a control with no carbon addition. Each reactor had a volume of 36.7 liters and a hydraulic detention time of 15.0 hr at the flow rate used in the study. All reactors were operated at a 20-day sludge age. Aerator equilibrium powdered-carbon concentration was calculated to be 3030 mg/liter during the first phase of the study.

The influent COD to each reactor was 230 mg/liter. The effluent from the control unit averaged 73.0 mg/liter of COD, with average COD values in the effluent from the test units ranging from 28.5 to 65.0 mg/liter. The amount of influent phenol to each reactor was 4.35 mg/liter. The amount of effluent phenol in the control unit was 0.018 mg/liter, whereas the amount of phenol effluent from the test units varied from 0.003 to 0.020 mg/liter.

Operating conditions for the second phase of the study were identical to those for the first phase except that the carbon dosage to the test units was increased to 200 mg/liter and the equilibrium carbon concentration in the aerator was increased to 6060 mg/liter. During this phase of study the effluent COD from the control unit averaged 58 mg/liter, and the effluent COD from the test unit ranged from 17 to 28 mg/liter. Phenol concentration from the control unit averaged 0.020 mg/liter, with the average amount of phenol in the effluent from the control units varying from 0.001 to 0.003 mg/liter.

The data presented in this study indicate that significant performance differences exist among different powdered activated carbons. In general the data indicated that a powdered-carbon—activated-sludge process could meet the target effluent

quality of 15 mg/liter for TOC, 24 mg/liter for COD, 6.3 mg/liter for ammonia, and 0.02 mg/liter for phenolics.

2. Exxon Research and Engineering, Florham Park, NJ
Bench-scale powdered-carbon—activated-sludge units were operated in order to evaluate the effect of carbon dosage on effluent quality. The test equipment consisted of 4.0-liter completely mixed aerators operated in parallel with varying carbon dosages. All units were controlled to a sludge age of 18 days.

Units were operated at aerator carbon concentrations of 25, 50, 75, 100, 200, 300, and 400 mg/liter. Performance data at these low carbon levels indicated that the powdered-carbon addition had very little effect on the removal of TOC, BOD_5, and NH_3. However, there was a slight decrease in effluent suspended-solids concentration.

Field tests were run to confirm the data obtained in the bench-scale studies. A full-scale activated-sludge unit was operated at an aerator concentration of 400 mg/liter of activated carbon. Performance data indicated that there was no improvement over the control unit, which had no powdered-carbon addition.

Subsequently the test unit aerator carbon concentration was increased to 1000 mg/liter. After two days of operation the units experienced severe organic shock loadings, which continued for the duration of the test. During this period the performance of the test unit was significantly better than that of the control units. Based on this experience it was concluded that PACT is most effective when used on a standby basis for low-cost treatment for organic shock loadings (96).

X. DATA SOURCES

FULL-SCALE ACTIVATED-CARBON SYSTEMS

1. "P-C Treatment Gets Industrial Trial," Environmental Science and Technology 8(1), 200—202 (January 1974).

2. "Carbon Advanced Waste Treatment Handles 20 MGD," Industrial Wastes 23(4), 40 (July/August 1977).

3. Baker, C. D., et al., "Recovering Para-Cresol from Process Effluent," Chemical Engineering Progress 69(8) 77, 78 (August 1973).

4. Baker, C. D., et al., "Recovery of p-Cresol from Process Effluent," Water 1973, AIChE Symposium Series 70, 686—692 (1973).

5. Becker, David L., and Stephen C. Wilson, "The Use of Activated Carbon for the Treatment of Pesticides and Pesticidal Wastes," Chap. 5 in Carbon Adsorption Handbook, edited by P. N. Cheremisinoff and F. Ellerbusch, Ann Arbor Science Publishers, Ann Arbor, MI, 1978.

6. Birkmeir, J. L., S. A. La Rocca, and R. E. Haulsee, "Activated Carbon Removes Pesticides from Wastewater at Research Facility," Industrial Wastes 24(5), 20—24 (1978).

7. Browning, Jon E., "Activated Carbon Bids for Wastewater Treatment Jobs," Chemical Engineering 77(18), 32—34 (Sept. 7, 1970).

8. Browning, Jon E., "New Water-Cleanup Roles for Powdered Activated Carbon," Chemical Engineering 79(4), 36—40 (Feb. 21, 1972).

9. Brunnots, V. A., R. T. Lynch, and G. R. Van Stone, "Granular Carbon Handles Concentrated Waste," Chemical Engineering Progress 69(8), 81—84 (August 1973).

10. Calgon Corporation, Industrial Water Pollution Control (in-house brochure).

11. Castorina, Thomas C., Jerome Haberman, and Jagadish Sharma, Charcoal Regeneration. Part I. Mechanism of TNT Adsorption, NTIS Microfiche, Technical Report ARLCD-TR-77065 (November 1977).

12. Catalytic Corp., Philadelphia, PA, computer printout compiled for Section 308 studies, Plants with Activated Carbon Data on Full-Scale or Test——Run for ESE (Mar. 16, 1979).

13. Cheremisinoff, Paul, and Angelo C. Morresi, "Carbon Adsorption Applications," pp. 1—54 in Carbon Adsorption Handbook, edited by P. N. Cheremisinoff and F. Ellerbusch, Ann Arbor Science Publishers, Ann Arbor, MI, 1978.

14. Davis, John C., "Activated Carbon Prime Choice to Boost Secondary Treatment," Chemical Engineering 84(8), 81—83 (Apr. 11, 1977).

15. Dehnert, J. F., "The Use of Powdered Activated Carbon with a Biodisc-Filtration Process for Treatment of Refinery Wastes," pp. 389—399 in Proceedings of the Second Open Forum on Management of Petroleum Refinery Wastewater, Tulsa, Oklahoma, EPA-600/2-78-0581 (March 1978).

16. DeJohn, Paschal B., and Alan D. Adams, "Treatment of Oil Refinery Wastewaters with Granular and Powdered Activated Carbon," pp. 16—23 in Proceedings of the 30th Purdue Industrial Waste Conference, Lafayette, Indiana, May 6—8, 1975, edited by J. M. Ball, Ann Arbor Science Publishers, Ann Arbor, MI, 1977.

17. Doll, Frederick, "Physical-Chemical Treatment of Munitions Plant Wastewater: A New Design Concept," pp. 36—40 in Proceedings of the Third Annual Conference on Treatment and Disposal of Industrial Wastewaters and Residues, Houston, TX, April 18—20, 1978, Information Transfer Inc., Rockville, MD, 1978.

18. EPA, Group II, Development Document for Effluent Limitations Guidelines for the Pesticide Chemicals Manufacturing, Point Source Category, EPA-400/1-78/060-e (PB-285 480) (April 1978).

19. EPA Technology Transfer Seminar Publication, Wastewater Treatment Systems. Upgrading Textile Operations to Reduce Pollution, Vol. 2 (October 1974).

20. Fox, R. D., Hydroscience, Inc., Knoxville, TN, provided W. L. Troxler with personal knowledge concerning activated-carbon systems, Dec. 12, 1979 (documented in confidential notebook in author's files).

21. Fox, R. D., R. T. Keller, and C. J. Pinamont, Recondition and Reuse of Organically Contaminated Waste Sodium Chloride Brines, EPA-R2-73-200 (May 1973).

22. Frings, Wilhelm, "Carbon Adsorption Knocks Down BOD_5 to 62 lb/day Limit," Chemical Processing 37(1), 7—9 (January 1974).

23. Gardner, Frank, Jr., and Alan Williamson, Naval Stores Wastewater Purification and Reuse by Activated Carbon Treatment, EPA-600/2-76-227 (October 1976).

24. Gumerman, Robert C., Russell L. Culp, and Sigmund P. Hansen, Estimating Water Treatment Costs, EPA-600/2-79-162a (August 1979).

25. Heck, Robert P., III, "Munitions Plant Uses Adsorption in Wastewater Treatment," Industrial Wastes 24(2), 35—39 (March/April 1978).

26. Henshaw, Tom B., "Adsorption/Filtration Plant Cuts Phenols from Effluent," Chemical Engineering 78(12), 47—49 (May 31, 1971).

27. Himmelstein, K. J., R. D. Fox, and T. H. Winter, "In-Place Regeneration of Activated Carbon," Chemical Engineering Progress 69(11), 65—69 (November 1973).

28. Hutton, David G., "Combined Powdered Activated Carbon-Biological Treatment," pp. 389—447 in Carbon Adsorption Handbook, edited by P. N. Cheremisinoff and F. Ellerbusch, Ann Arbor Science Publishers, Ann Arbor, MI, 1978.

29. Hutton, David G., and Stanley Temple, "Priority Pollutant Removal: Comparison of Du Pont PACT Process and Activated Sludge," Proceedings of the Industrial Wastes Symposium, 52nd Water Pollution Control Federation Meeting, Houston, TX, Oct. 7—12, 1979.

30. Iowa Army Ammunition Plant, Carbon Column System Removal Efficiency Study, Study No. 24-033-73/74, Burlington, IA (May 2—June 22 1973).

31. Jett, G. M., EPA Effluent Guidelines Division, Washington, D.C., personal communication with R. Turner, EPA, IERL, Cincinnati, OH, Oct. 3, 1979.

32. Josephson, Julian, "Activated Carbon Makes Water Clean," Environmental Science and Technology 10(10), 974, 975 (October 1976).

33. Loop, Gary C., Refinery Effluent Water Treatment Plant Using Activated Carbon, EPA-660/2-75-020 (PB 244 389) (June 1975).

34. Löwenbach, W., and J. Schlesinger, Nitrobenzene/Aniline Manufacture: Pollutant Predicton and Abatement, Metrek Division of the MITRE Corp., MTR-7828 (May 1978).

35. Marek, Anton C., and Michael A. Pikulin, "Startup and Operation of a 20 MGD Activated Carbon Treatment System," pp. 105—112 in Proceedings of 33rd Annual Purdue Industrial Waste Conference, Lafayette, Indiana, May 9—11, 1978, edited by J. M. Bell, Ann Arbor Science Publishers, Ann Arbor, MI, 1979.

36. McCrodden, Bruce A., Treatment of Refinery Wastewater Using a Filtration-Activated Carbon System, EPA-60012-79-066 (March 1979).

37. Minor, Paul S., "Organic Chemical Industry's Waste Waters," Environmental Science and Technology 8(7), 620—625 (July 1974).

38. Monsanto Research Corp., Wastewater Treatability Manual for EPA (unpublished).

39. Myers, Leon H., and Frank Mayhue, "Advanced Industrial Waste Treatment Processes for the Petroleum Refining/Organic Chemical Industry," Water 1973, AIChE Symposium Series 70(136), 568—576 (1973).

40. O'Brien, J. E., et al., "Treatment of Wastes from Tank Truck Cleaning," Pollution Engineering 9(4), 44—48 (April 1977).

41. Parmele, C., Hydroscience, Inc., personal communication with Donald Kemp, Metcalf and Eddy, Boston, MA, taken from confidential activated carbon marketing survey, December 1979.

42. Parmele, C., Hydroscience, personal communication with Ronald J. Turner, EPA, regarding information contained in trip reports by Environmental Science and Engineering.

43. Parmele, C., Hydroscience, telephone call to Gary Van Stone, Calgon Corp., Pittsburgh, PA, June 11, 1979 (documented in confidential notebook in author's file).

44. Prosche, M. A., "Activated Carbon Treatment of Combined Storm and Process Waters," pp. 399—410 in Proceedings of the Open Forum on Management of Petroleum Refinery Wastewaters, Tulsa, Oklahoma, Jan. 26—29, 1976, Francis S. Manning, editor, published by Robert S. Kerr Environmental Research Laboratories, Ada, Oklahoma (n.d.).

45. Rey, G., M. Dick, and P. Des Rosiers, "EPA's R&D Program for Activated Carbon," Chemical Engineering Progress 69(11), 45—47 (November 1973).

46. Rizzo, J. L., "Granular Carbon for Wastewater Treatment," Water and Sewage Works 18(8), 238—240 (August 1971).

47. Rizzo, Joyce, "Case History: Use of Powdered Activated Carbon in an Activated Sludge System," pp. 359—374 in Proceedings of the Open Forum on Management of Petroleum Refinery Wastewater, Tulsa, Oklahoma, Jan. 26—29, 1976, Francis S. Manning, editor, published by Robert S. Kerr Environmental Laboratories, Ada, Oklahoma (n.d.).

48. Robertaccio, Francis L., "Combined Powdered Activated Carbon-Biological Treatment: Theory and Results," pp. 325—343 in Proceedings of the Second Open Forum on Management of Petroleum Refinery Wastewater, Tulsa, Oklahoma, EPA-600/2-78-058 (March 1978).

49. Rodman, Clark A., Edward L. Shunney, and Anthony Perrotti, "Biological Regeneration of Activated Carbon," pp. 449—484 in Carbon Adsorption Handbook, edited by Paul N. Cheremisinoff and Fred Ellerbusch, Ann Arbor Science Publishers, Ann Arbor, MI, 1978.

50. Roy, C., and B. Volesky, "Activated Carbon Adsorption Process for Purification of Textile Wastewater," Textile Chemist and Colorist 10(5), 26—33 (1978).

51. Schimmel, C., and D. B. Griffin, Treatment and Disposal of Complex Industrial Wastes, EPA-600/2-76-123 (November 1976).

52. Schroeder, James W., and H. Charles Naso, "A New Method of Treating Coke Plant Wastewater," Iron and Steel Engineer 53(12), 60—66 (December 1976).

53. Skovornek, Herbert, and David Becker, Pollution Control by Adsorption, paper presented at American Institute of Chemical Engineers Annual Meeting, November 1977, New York City.

54. Skovronek, S. Herbert, Marshall Dick, and Paul E. des Rosiers, Selected Uses of Activated Carbon for Industrial Wastewater Pollution Control, paper presented at the Second Annual Conference on New Advances in Separation Technology, Cherry Hill, NJ, Sept. 23—24, 1976; reprinted in Industrial Water Engineering 14(3), 6—13 (May/June 1977).

55. South Carolina Department of Health Water Pollution Control Permit File.

56. Thomas, Ken, Beckman Instrument Company, Porterville, CA, letter dated Aug. 3, 1979, to W. L. Troxler, Hydroscience (documented in confidential notebook in author's files).

57. Thomas, S. H., and D. R. Walsh, An Industrial Wastewater Recirculation System for the Fibrous Glass Textile Industry, paper presented at the Symposium on Textile Industry Technology, Williamsburgh, VA, Dec. 8, 1978.

58. Troxler, W. L., telephone call to Terry Borders, South Carolina Department of Health, Columbia, SC, Sept. 11, 1979 (documented in confidential notebook in author's files).

59. Troxler, W. L., telephone call to Chuck Whittier, Region 6, Dallas, TX, Aug. 17, 1979 (documented in confidential notebook in author's files).

60. Troxler, W. L., telephone call to Bob Dicks, Texas Water Quality Control Board, Austin, TX, Aug. 22, 1979).

61. Troxler, W. L., telephone call to Larry Nadler, New York Department of Environmental Conservation, Albany, NY, Sept. 10, 1979 (documented in confidential notebook in author's files).

62. U. S. Environmental Protection Agency, Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Synthetic Resins Segment of the Plastics and Synthetic Materials Manufacturing Point Source Category, EPA 440/1-74-010-a (March 1974).

63. West Virginia Department of Natural Resources Water Pollution Control Permit File.

64. Wiseman, S., and B. T. Bawden, "Removing Refractory Compounds from Waste Water," Chemical Engineering Progress 73(5), 60—64 (May 1977).

65. Wroniewicz, V. S., "Controlling Chlorinated Benzene Compounds in Plant Wastewaters," Pollution Engineering 10(11), 43, 44 (November 1978).

66. Zanitsch, R. H., and J. A. Rizzo, Use of Granular Activated Carbon for Industrial Wastewater Treatment, paper presented at the 48th Annual Meeting of the Ohio Water Pollution Control Conference, Toledo, OH, June 12—14, 1974.

PILOT- AND BENCH-SCALE ACTIVATED-CARBON STUDIES

67. Alperin, E. S., et al., "Carbon Adsorption as a Recovery Technology," Proceedings of the Industrial Wastes Symposia, 52nd Water Pollution Control Federation Meeting, Houston, TX, Oct. 7—12, 1979.

68. Argaman, Yerachmiel, and Giovanni M. Sassa, "Treatment of Chlorinated Hydrocarbons Wastewater by Activated Carbon Adsorption with Steam Regeneration," Progress in Water Technology 9(1), 65—73 (1977).

69. Dehnert, J. F., "The Use of Powdered Activated Carbon with a Biodisc-Filtration Process for Treatment of Refinery Wastes," pp. 389—399 in Proceedings of the Second Open Forum on Management of Petroleum Refinery Wastewater, Tulsa, Oklahoma, EPA-600 12-78-058 (March 1978).

70. DeJohn, Paschal B., and Alan D. Adams, "Treatment of Oil Refinery Wastewaters with Granular and Powdered Activated Carbon," pp. 216—232 in Proceedings of the 30th Purdue Industrial Waste Conference, Lafayette, Indiana, May 6—8, 1975, edited by J. M. Bell,Ann Arbor Science Publishers, Ann Arbor, MI, 1977.

71. Demek, Mary M., et al., Studies on the Regeneration of Activated Carbon for Removal of α-TNT from Wastewaters, Edgewood Arsenal Technical Report EC-TR-74008 (May 1974).

72. Grieves, C. G., et al., Effluent Quality Improvement by Powdered Activated Carbon in Refinery Activated Sludge Processes, paper presented at API Refining Department 42nd Midyear Meeting, Chicago, IL, May 11, 1977.

73. Hale, Jack H., Leon H. Myers, and Thomas E. Short, Jr., "Pilot Plant Activated Carbon Treatment of Petroleum Refinery Wastewater," pp. 375—397 in Proceedings of the Open Forum on Management of Petroleum Refinery Wastewaters, Tulsa, Oklahoma, Jan. 26—29, 1976, Francis S. Manning, editor, published by Robert S. Kerr Environmental Research Laboratories, Ada, OK (n.d.).

74. Huang, Ju Chang, and Michael G. Hardie, "Treatment of Refinery Waste by Physico-chemical Processes," Journal of the Sanitary Engineering Division, ASCE 97(4), 467—479 (August 1971).

75. Hutton, David G., "Combined Powdered Activated Carbon-Biological Treatment," pp. 389—447 in Carbon Adsorption Handbook, Ann Arbor Science Publishers, Ann Arbor, MI, 1978.

76. Hydroscience, Inc., unpublished data on 1,2-dichloroethane adsorption by granular activated carbon (1979).

77. Hydroscience, Inc., unpublished data on multicomponent adsorption by granular activated carbon (1979).

78. Hydroscience, Inc., unpublished data on phenol adsorption by granular activated carbon (1979).

79. Jain, K. K., Industrial Waste Treatment Using Adsorption-Oxidation Process, prepared for the Petroleum and Environmental Technology Division of the U.S. Army Mobility Equipment R&D Command (MERADCOM), Fort Belvoir, VA, Dec. 7,1978.

80. Kroop, Ronald H., "Treatment of Phenolic Aircraft Paint Stripping Wastewater," pp. 1071—1087 in Proceedings of the 28th Purdue Industrial Waste Conference, Lafayette, Indiana, May 1—3, 1973, edited by J. M. Bell, Purdue University Engineering Extension Series No. 142, Lafayette, IN, 1973.

81. Lang, E. W., W. G. Timpe, and R. L. Miller, Activated Carbon Treatment of Unbleached Kraft Effluent for Reuse, EPA-660/2-75-004 (April 1975).

82. Lawson, C. T., A. C. Booth, and J. C. Hovious, "Activated Carbon for Tertiary Treatment of Organic Chemical Wastewaters—Bench and Pilot-Scale Experience," pp. 22—31 in Proceedings of the 33rd Purdue Industrial Waste Conference, Lafayette, Indiana, May 9—11, 1978, edited by J. M. Bell, Ann Arbor Science Publishers, Ann Arbor MI, 1979.

83. Lawson, Cyron T., and John A. Fisher, "Limitations of Activated Carbon Adsorption for Upgrading Petrochemical Effluents," Water-1973, AIChE Symposium Series 70(136), 577—584 (1973).

84. Lawson, C. T., and J. C. Hovious, "Cautions and Limitations on the Application of Activated Carbon Adsorption to Organic Chemical Wastewaters," pp. 345—358 in Proceedings of the Open Forum on Management of Petroleum Refinery Wastewaters, Tulsa, Oklahoma, Jan. 26—29, 1976, Francis S. Manning, editor, published by Robert S. Kerr Environmental Research Laboratories, Ada, OK (n.d.).

85. Leipzig, Neil A., and Melvin R. Hockenbury, Powdered Activated Carbon/Activated Sludge Treatment of Chemical Production Wastewaters, paper presented at 34th Purdue Industrial Waste Conference, Lafayette, IN, May 10—12, 1979.

86. Macnaughton, Michael G., and Thomas B. Stauffer, Treatment of N-nitrosodimethylamine Contaminated Waste with Activated Carbon, NTIS AD/A-039 229 (November 1977).

87. Monsanto Research Corporation, Wastewater Treatability Manual (unpublished).

88. Perrotti, Anthony E., Activated Carbon Treatment of Phenolic Paint Stripping Wastewater, NTIS AD-A022 982, August 1975.

89. Pfeffer, Fred M., Wyman Harrison, and Leo Raphaelian, "Organics Reduction Through Add-On Activated Carbon at Pilot Scale," pp. 403—418 in Proceedings of the Second Open Forum on Management of Petroleum Refinery Wastewater, EPA-600 12-78-058e (March 1978).

90. Poon, Calvin P.C., and Philip P. Virgadamo, Anaerobic-Aerobic Treatment of Textile Wastes with Activated Carbon, EPA-R2-73-248 (May 1973).

91. Raphaelian, L. A., and W. Harrison, Trace Organics Variation Across the Wastewater Treatment System of a Class B Refinery, EPA-600 17-78-125 (June 1978).

92. Schulte, G. R., Robert C. Hoehn, and Clifford W. Randall, "The Treatability of a Munitions Manufacturing Waste with Activated Carbon," pp. 150—162 in Proceedings of the 28th Purdue Industrial Waste Conference, Lafayette, Indiana, May 1—3, 1973, edited by J. M. Bell, Purdue University Engineering Extension Series No. 142, Lafayette, IN, 1973.

93. Shindala, Adnan, et al., "Treatment of Wastes Generated from the Production of Methyl Parathion and Potassium Nitrate," pp. 41—48 in Proceedings of the Third Annual Conference on Treatment and Disposal of Industrial Wastewaters and Residues, Houston, Apr. 18—20, 1978, Information Transfer, Inc., Rockville, MD, 1978.

94. Skovronek, Herbert S., Marshall Dick, and Paul E. des Rosiers, Selected Uses of Activated Carbon for Industrial Pollution Control, paper presented at the Second Annual Conference on New Advances in Separation Technology, Cherry Hill, NJ, Sept. 23—24, 1976; reprinted in Industrial Water Engineering 14(3), 6—13 (May/June 1977).

95. Stenstrom, Michael K., and Colin G. Grieves, "Enhancement of Oil Refining Activated Sludge by Additon of Powdered Activated Carbon," pp. 196—205 in Proceedings of the 32nd Purdue Industrial Waste Conference, Lafayette, IN, May 10—12, 1977, edited by J. M. Bell, Ann Arbor Science Publishers, Ann Arbor, MI, 1978.

96. Thibault, G. J., K. D. Tracy, and J. B. Wilkinson, "PACT Performance Evaluated," Hydrocarbon Processing 56(5), 143—146 (May 1977).

97. Young, D. A., and B. G. Parker, "Removal of Methylenedianiline from Chemical Plant Wastewater," pp. 206—210 in Proceedings of the Third Annual Conference on Treatment and Disposal of Industrial Wastewaters, Houston, Apr. 18—20, 1978, Information Transfer, Inc., Rockville, MD, 1978.

98. Zogorski, J. S., and S. D. Faust, "Removing Phenols via Activated Carbon," Chemical Engineering Progress 5(73), 65, 66 (May 1977).

MISCELLANEOUS

99. Al-Bahrani, K. S., and R. J. Martin, "Adsorption Studies Using Gas-Liquid Chromatography-I. Effect of Molecular Structure," Water Research 10(8), 731—736 (Aug. 1976).

100. Bernardin, Frederick E., Jr., and Emery M. Froelich, "Practical Removal of Toxicity by Adsorption," pp. 548—560 in Proceedings of the 30th Purdue Industrial Waste Conference, Lafayette, Indiana, May 6—8, 1975, edited by J. M. Bell, Ann Arbor Science Publishers, Ann Arbor, MI, 1977.

101. Calgon Corporation, Guidelines for Granular Activated Carbon Wastewater Treatment Systems, Activated Carbon Applications Bulletin 20-4b (in-house brochure) (1973).

102. Crittenden, John C., and Walter J. Weber, "Model for Design of Multicomponent Adsorption Systems," Journal of the Environmental Engineering Division, ASCE 104(6), 1175—1195 (December 1978).

103. Dobbs, Richard A., Richard J. Middendorf, and Jesse M. Cohen, Carbon Adsorption Isotherms for Toxic Organics, Municipal Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH (May 1978).

104. El-Dib, M. A., F. M. Ramadan, and Magdy Ismail, "Adsorption of SEVIN and BAYGON on Granular Activated Carbon," Water Research 9(9), 795—798 (September 1975).

105. EPA Technology Transfer Publication, Process Design Manual for Carbon Adsorption (October 1973).

106. Famularo, Jack, Ajit Singh Panu, and James A. Mueller, Predicting of Carbon Column Performance from Pure-Solute Data, Hydroscience, Inc., R&D Report No. 79-128 (Nov. 21, 1978).

107. Ford, Davis L., "Current State of the Art of Activated Carbon Treatment," pp. 295—344 in Proceedings of the Open Forum on Management of Petroleum Refinery Wastewaters, Tulsa, Oklahoma, Jan. 26—29, 1976, Francis S. Manning, editor, published by Robert S. Kerr, Environmental Research Laboratories, Ada, OK (n.d.).

108. Guisti, D. M., R. A. Conway, and C. T. Lawson, "Activated Carbon Adsorption of Petrochemicals," Journal of the Water Pollution Control Federation 46(5), 947—965 (May 1974).

109. Hager, D. G., "Industrial Wastewater Treatment by Granular Activated Carbon," Industrial Water Engineering 11(1), 14—28 (January/February 1974).

110. Hager, D. G., "Waste Water Treatment via Activated Carbon," Chemical Engineering Progress 13(5), 57—60 (October 1976).

111. Hager, D. G. and J. L. Rizzo, Removal of Toxic Organics from Wastewater by Adsorption with Granular Activated Carbon, paper presented at EPA Technology Transfer Session on Treatment of Toxic Chemicals, Atlanta, Apr. 19, 1974.

112. Hemphill, Louis, Thermal Regeneration of Activated Carbon, EPA-600/2-78-103 (May 1978).

113. Huang, Ju-Chang, and Charles T. Steffens, "Competitive Adsorption of Organic Materials by Activated Carbon," pp. 107—121 in Proceedings of the 31st Purdue Industrial Waste Conference, Lafayette, May 4—6, 1976, edited by J. M. Bell, Ann Arbor Science Publishers, Ann Arbor, MI, 1977.

114. ICI Americas Inc., Powdered Hydrodarco® Activated Carbons for Wastewater Treatment, 901-7 (in-house brochure) (October 1979).

115. ICI Americas, Inc., Granular Hydrodarco® Activated Carbons for Wastewater Treatment, 903-1 (in-house brochure) (October 1979).

116. Jain, K. S., and Vernon L. Snoeyink, "Adsorption from Bisolute Systems on Active Carbon," Journal of the Water Pollution Control Federation 45(12), 2463—2479 (December 1973).

117. Keinath, Thomas M., "Design and Operation of Activated Carbon Adsorbers Used for Industrial Wastewater Decontamination," Water-1976 I. Physical, Chemical Wastewater Treatment, AIChE Symposium Series 73(66), 1—7 (1976).

118. Keinath, Thomas M., and Robert P. Carnahan, Mathematical Modeling of Heterogeneous Sorption in Continuous Contactors for Wastewater Decontamination, prepared for U.S. Army Medical R&D Command, Contract No. ADA-17-72-6-2034 (December 1973).

119. Lawrence, John, and Helen M. Tosine, "Adsorption of Polychlorinated Biphenyls from Aqueous Solutions and Sewage," Environmental Science and Technology 10(4), 381—383 (April 1976).

120. Liapis, A. I., and D. W. T. Rippin, "The Simulation of Binary Adsorption in Activated Carbon Columns Using Estimates of Diffusional Resistance Within the Carbon Particles Derived from Batch Experiments," Chemical Engineering Science 33(5), 593—600 (May 1978).

121. Martin, R. J., and K. S. Al-Bahrani, "Adsorption Studies Using Gas-Liquid Chromatography-II. Competitive Adsorption," Water Research 11(11), 991—999 (November 1977).

122. Matthews, John E., Treatment of Petroleum Refinery, Petrochemical and Combined Refinery, Petrochemical and Combined Industrial-Municipal Wastewaters with Activated Carbon, EPA-600/2-78-200 (September 1978).

123. Nony, Charles R., Edward J. Treglown, and Malcolm C. Bowman, "Removal of Trace Levels of 2-Acetylaminofluorene from Wastewater," The Science of the Total Envionment 4, 155—163 (1975).

124. Parkash, Sat, "Adsorption of Cationic Pesticides (Diquat and Paraquat) from Aqueous Solution by Activated Carbon," Carbon 12(5), 483—491 (May 1974).

125. Radke, C. J., and J. M. Prausnitz, "Adsorption of Organic Solutes from Dilute Aqueous Solution on Activated Carbon," Industrial Engineering Chemistry Fundamentals 11(4), 445—451 (April 1972).

126. Reimers, R. S., A. J. Englande, and H. B. Miles, "A Quick Method for Evaluating the Suitability of Activated Carbon Adsorption for Wastewaters," pp. 395—408 in Proceedings of the 31st Purdue Industrial Waste Conference, Lafayette, Indiana May 4—6, 1976, Ann Arbor Science Publishers, Ann Arbor, MI, 1977.

127. Rizzo, Joseph L., and Austin R. Shepherd, "Treating Industrial Wastewater with Activated Carbon," Chemical Engineering 84(1), 95—100 (Jan. 3, 1977).

128. Shell, G. T., "Powdered Carbon Regeneration in a Fluid Bed Furnace," Water 1974, AIChE Symposium Series, 144(70), 371—377 (1974).

129. Shell, G. T., et al., "Regeneration of Activated Carbon," pp. 167—178 in Progress in Water Technology, Vol. I, edited by W. W. Eckenfelder and L. K. Cecil, Pergamon Press, New York, 1972.

130. Smith, C. E., "Principles and Practice of Granular Carbon Reactivation," pp. 179—186 in Progress in Water Technology, Vol. I, edited by W. W. Eckenfelder and L. K. Cecil, Pergamon Press, New York, 1972.

131. Tewsbury, T. L., N. K. Reed, and G. R. Smithson, "Development of a Fluidized-Bed Technique for the Regeneration of Powdered-Activated Carbon," Water 1974, AIChE Symposium 144(70), 360—370 (1974).

132. Wagner, Norman J., John R. Tutchko, and Robert F. Deithorn, Control of Toxic Emissions from the Thermal Reactivation of Activated Carbon, paper presented at 34th Purdue Industrial Waste Conference, Lafayette, IN, May 8—10, 1979.

133. Ward, Thomas M., and Forrest W. Getzen, "Influence of pH on the Adsorption of Aromatic Acids on Activated Carbon," Environmental Science and Technology 4(1), 64—67 (January 1970).

134. Weber, Walter J., and J. Carrell Morris, "Equilibria and Capacities for Adsorption on Carbon," Journal of the Sanitary Engineering Division, ASCE, 90(3), 79—107 (June 1964).

135. Westvaco Corporation, Product Data Bulletin G-100 (in-house brochure) (September 1977).

136. Westvaco Corporation, Product Data Bulletin G-101, (in-house brochure) (September 1977).

137. Westvaco Corporation, Product Data Bulletin G-102 (in-house brochure) (September 1977).

138. Westvaco Corporation, Product Data Bulletin P-102 (in-house brochure) (April 1978).

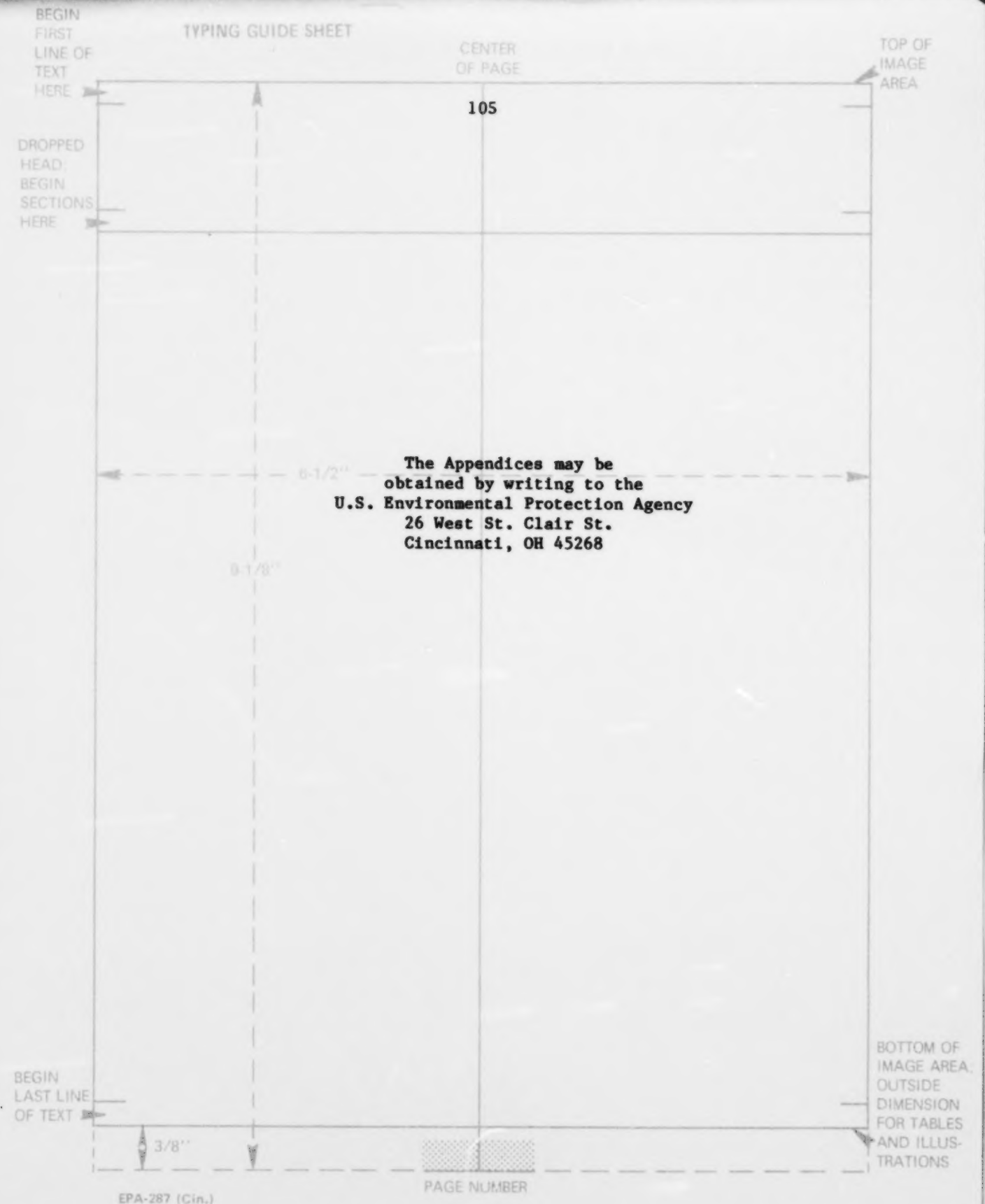
139. Westvaco Corporation, Product Data Bulletin P-105 (in-house brochure) (April 1978).

140. Whitehouse, James David, A Study of the Removal of Pesticides from Water, NTIS PB-242 971 (December 1967).

141. Witco Chemical Company, Witcarb® Activated Carbon, Bulletin W-118 (in-house brochure) (October 1976).

142. Zanitsch, R. H., "Granular Carbon Reactivation: State-of-the-Art," pp. 419—439 in Proceedings of the Second Open Forum on Management of Petroleum Refinery Wastewater, Tulsa, OK, EPA-60012-78-058 (March 1978).

143. Mayhew, J. J., Chemical Manufacturers Association, letter to Ronald J. Turner EPA, IERL, Cincinnati, OH, July 15, 1980, containing comments on draft of this report "Survey of Industrial Application of Aqueous-Phase Activated-Carbon Adsorption for Control of Pollutant Compounds from Manufacture of Organic Compounds."


BEGIN FIRST LINE OF TEXT HERE
TYPING GUIDE SHEET
CENTER OF PAGE
TOP OF IMAGE AREA
105
DROPPED HEAD: BEGIN SECTIONS HERE
6-1/2"
9-1/8"
The Appendices may be
obtained by writing to the
U.S. Environmental Protection Agency
26 West St. Clair St.
Cincinnati, OH 45268
BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA. OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"
PAGE NUMBER
EPA-287 (Cin.)
(4-76)